



Interaction Controls on Sediment Entrainment in GLOF-Related Cascading Mass Flows: Evidence from Central Asian High-Mountain Catchments

GEO 511 Master's Thesis

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Abstract

Glacial lake outburst floods (GLOFs) represent one of the most significant natural hazards in Central Asia's high mountain regions. In the northern Tien Shan, particularly in the Ile-Alatau of south-eastern Kazakhstan, the combination of rapid glacier retreat, an increasing number of glacial lakes, and steep, sediment-rich catchments creates a high hazard potential. GLOFs in this region frequently evolve into cascading mass flows, whose volume, dynamics, and destructive potential are largely controlled by sediment entrainment along the flow path. Despite its central importance, sediment entrainment is still insufficiently considered in many existing hazard assessments.

This study aims to systematically investigate the processes of sediment entrainment in GLOF-induced cascading mass flows in the Ile-Alatau region, with a focus on the dominant controlling factors at the catchment scale. A combined approach is employed that integrates a conceptual synthesis of documented historical GLOF events with an empirical analysis of the hydrological, geomorphometric and sedimentological factors involved. Using digital elevation data and statistical models, the factors governing sediment entrainment along the entire flow path are quantified based on several well-documented GLOF events across different catchments.

The results suggest that the entrainment of sediments is primarily influenced by the interplay of hydrological factors (notably discharge and flow velocity), geomorphometric conditions (e.g. channel gradient, valley confinement, and longitudinal connectivity), and the spatial distribution of unconsolidated sediments. Significant differences in the magnitude and spatial distribution of sediment entrainment are observed between catchments, reflecting their different topographic and sedimentological configurations. These findings emphasise the need to explicitly consider sediment dynamics when assessing GLOF hazards and provide a process-based foundation for more accurate, region-specific modelling and risk assessment in high mountain environments.

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1. Introduction

1.1. Context

High mountain regions worldwide are highly vulnerable to gravitational natural hazards. The combination of steep slopes, unstable sediment deposits, and extreme climatic conditions promotes mass movements (Mergili & Schneider, 2011). Among the most hazardous phenomena are glacial lake outburst floods (GLOFs), which involve the sudden release of large volumes of water from glacial lakes. Such events are typically triggered by the failure of moraine- or ice-dammed lakes or by external disturbances such as avalanches, rockfalls, or earthquakes (Zaginaev et al. 2019).

In Central Asia, particularly in the Tien Shan and Pamir mountain systems, GLOFs have been documented for more than a century. A particularly noticeable increase in destructive events occurred during the 1970s and 1980s. This phase coincided with pronounced glacier retreat and the rapid formation of moraine lakes (Bolch et al. 2011; Harrison et al. 2018). While the frequency of documented GLOFs has not increased steadily since then (Falátková, 2016), the potential for hazards remains high. Climate change is causing glaciers to shrink and permafrost to degrade, making moraine dams more unstable and promoting the formation of new glacial lakes (Chen et al. 2024; Sydyk et al. 2025; Zheng et al. 2021). Studies indicate that lakes situated in steep catchment areas with high meltwater inflow pose a significant risk of future outbursts (Chen et al. 2024; Zaginaev et al. 2019).

GLOFs in Central Asia differ significantly from ordinary floods, in terms of both their dynamics and their geomorphological impact. Previous observations and case studies have shown that water released from moraine lakes often interacts with large quantities of unconsolidated glacial and paraglacial sediments along steep valley sides (Harrison et al. 2018; Zaginaev et al. 2019). These interactions mobilise large volumes of unconsolidated sediment (sediment entrainment), significantly increasing flow volume, mobility and destructive potential and often transforming the initial water outburst into debris-flow-like mass movements (Westoby et al. 2014a; Zaginaev et al. 2019). This results in significant geomorphological changes along the runoff paths, including deep erosion, sediment accumulation, and massive sediment redistribution in valley areas (Chen et al. 2024; Zaginaev et al. 2019). The geomorphological effects of these processes often extend far beyond the immediate vicinity of the lake, endangering infrastructure and settlements in the lower catchment area (Cook et al. 2018; Zaginaev et al. 2019).

In Kazakhstan, GLOFs pose a significant natural hazard, particularly in the Ile-Alatau Mountains of the northern Tien Shan. The accelerated retreat of glaciers due to climate change has resulted in the creation of numerous new glacial lakes in areas that have recently experienced deglaciation (Mussina et al. 2024; Shahgedanova et al. 2024). Many of these lakes are situated above steep valleys and in close proximity to densely populated areas. Their location above the city of Almaty is particularly critical, posing a considerable risk to the population and infrastructure (Mussina et al. 2024). GLOF events in the Ile-Alatau region have repeatedly caused severe damage to transport routes, water supply facilities, and settlement structures in the past. Notable examples include Lake Kishi Almaty, Big Almaty Lake, and Mynzhylky, which have already attracted attention

due to dam failures or external triggers (Medeu et al. 2022; Zaginaev et al. 2019). Current risk assessments show that the number of potentially dangerous lakes is increasing, particularly above Almaty (Blagovechshenskiy, Viktor et al. 2015).

Despite the long-standing tradition of researching GLOFs in Kazakhstan, many historical events occurred before high-resolution remote sensing data became available and therefore lack systematic post-event documentation. This has significantly constrained the reconstruction of complete flow paths and hindered a detailed understanding of flow evolution and sediment dynamics. However, recent studies have begun to address these gaps. For example, Shahgedanova et al. (2024) developed a regional database of debris flows in the northern Tien Shan, including the Ile-Alatau range. Although the analysis focuses on rainfall-triggered debris flows, the results highlight sediment entrainment as a key process controlling downstream flow characteristics, which is also highly relevant for large, cascading mass movements following GLOFs in high-mountain catchments (Shahgedanova et al. 2024).

Against this backdrop, the present thesis aims to investigate sediment entrainment as a defining feature of GLOF-induced mass flows in south-eastern Kazakhstan, with a primary focus on the Ile-Alatau range. The region's pronounced relief energy, abundant unconsolidated sediments, and high geomorphic activity provide favourable conditions for substantial entrainment volumes. The study applies a combined conceptual, geomorphometric and empirical approach, integrating documented GLOF case studies with geomorphometric terrain analysis and statistical modelling to identify dominant controls on sediment entrainment along complete flow paths.

1.2. Motivation and Research Gap

Against the background of the high GLOF hazard in Central Asia, previous research in Kazakhstan and neighbouring regions has predominantly concentrated on source-lake characteristics and initiation mechanisms, including lake volume, dam composition and breach-triggering processes (e.g. Walder and Costa, 1996; Bolch et al. 2011; Blagovechshenskiy, Viktor et al. 2015). While these approaches are essential for identifying potentially dangerous lakes, they provide limited insight into the downstream evolution of GLOF events in steep, sediment-rich alpine catchments.

Evidence from post-event analyses in the Tien Shan and other high mountain regions demonstrates that sediment entrainment along the flow path can substantially amplify both the volume and destructive potential of GLOFs (Allen et al. 2016; Emmer et al. 2022; Westoby et al. 2014b). In several documented events, the amount of entrained sediment exceeded the volume of the initially released water, resulting in flow behaviour that closely resembles debris flows rather than clear-water floods (Allen et al. 2016). As shown by Iverson et al. (2011), strong feedbacks between erosion, momentum, and flow depth can further intensify this transformation. Despite its importance, sediment entrainment is commonly treated as an implicit component of GLOF hazard assessments and is rarely analysed as a key controlling process in its own right (Emmer et al. 2022; Westoby et al. 2014b).

This shortcoming is particularly apparent in the Ile-Alatau range, where geomorphic conditions strongly favour erosion during high-magnitude flood events. The region is characterised by steep valley gradients, narrow channel sections, and widespread deposits of unconsolidated moraines, talus slopes, and glaciofluvial sediments (Bolch et al. 2019; Medeu et al. 2022). Nevertheless, existing studies in the Ile-Alatau region have largely focused on glacial lake inventories, hazard

classifications, or reconstructions of individual events, with limited emphasis on catchment-scale sediment dynamics (Medeu et al. 2022; Zaginaev et al. 2016).

More generally, comparative catchment-scale studies that explicitly link GLOF source characteristics with geomorphometric controls along the entire flow path and observed erosion patterns across multiple events remain scarce in southeastern Kazakhstan. As a result, the role of spatial variability in topography, channel morphology, and sediment availability in controlling GLOF behaviour is still poorly constrained. This lack of process-based understanding limits the reliability of regional hazard assessments and hampers the application of numerical flow models in Central Asia, as highlighted by Emmer et al. (2022) and Zaginaev et al. (2016). In particular, systematic, multi-event, catchment-scale analyses that explicitly relate observed sediment entrainment patterns to geomorphometric controls along complete GLOF flow paths remain limited in southeastern Kazakhstan.

Closing this research gap requires a process-oriented, catchment-scale approach to GLOF dynamics. Accordingly, this thesis focuses on documented GLOF events in the Ile-Alatau region, with particular emphasis on sediment entrainment along complete flow paths from lake outlets to downstream depositional zones. Through the systematic analysis of interactions between hydrological forcing, geomorphometric conditions and sediment availability, sediment entrainment is treated as an emergent, process-coupled phenomenon whose efficiency depends on flow intensity, terrain characteristics and sediment connectivity along the flow path. This study aims to improve understanding of GLOF evolution in the high mountain catchments of Kazakhstan and to support more robust, regionally adapted hazard assessments by providing a process-based understanding of sediment dynamics rather than direct parametrisation for hazard models.

1.3. Objectives

The main objective of this study is to improve the process-based understanding of sediment entrainment processes in cascading mass flows following glacial lake outburst floods in the Ile-Alatau mountain range. The methodological framework integrates documented GLOF case studies with catchment-scale terrain analysis and statistical modelling to systematically relate sediment entrainment patterns to hydrological, geomorphometric, and sedimentological controls. To achieve this objective, the study will:

- Analyse how hydrological, topographic, and sedimentological factors jointly control sediment entrainment in GLOF-related mass flows
- Compare sediment entrainment characteristics and controlling controls between individual catchments within the Ile-Alatau mountain range
- Integrate empirical hydrological analyses with geomorphometric terrain assessment to identify the interaction of dominant controls governing sediment entrainment

1.4. Research Questions and Hypothesis

To address this research gap and to improve the understanding of sediment entrainment in GLOF-related cascading mass flows, this study aims to answer the following research questions:

1. Which hydrological, geomorphometric and sedimentological factors and their interactions influence sediment entrainment in cascading mass flows following GLOFs in the Ile-Alatau mountain range?
2. How do sediment entrainment characteristics and their controlling hydrological and geomorphological factors differ between individual catchments within the Ile-Alatau mountain range?
3. What insights can be derived from an integrated empirical and conceptual analysis of documented GLOF events in the Ile-Alatau region regarding sediment entrainment processes and their dominant hydrological and geomorphometric controls?

Based on the research questions outlined above, this study tests the following hypothesis:

Sediment entrainment in GLOF-related cascading mass flows in the Ile-Alatau mountain range is primarily controlled by the interaction between hydrological forcing and geomorphometric conditions along the flow path, while sediment availability modulates the magnitude and spatial patterns of erosion and deposition, resulting in systematic, catchment-specific patterns.

1.5. Structure of the Thesis

This thesis begins with a synthesis of the current state of research on GLOFs and sediment entrainment, outlining key processes and triggering mechanisms, as well as research gaps. Next, the study area in the Ile-Alatau mountain range is introduced to provide the regional, glaciological, and geomorphological context relevant to sediment availability and entrainment potential. On this foundation, a conceptual understanding of sediment entrainment is developed based on documented case studies and previous research. The empirical analysis combines the hydrological characteristics of documented GLOF events with geomorphometric terrain analyses derived from orthophotos and digital terrain models. This combination identifies the factors that control sediment entrainment at the catchment scale. Finally, the results are synthesized and discussed in the context of existing literature. The study concludes with implications for GLOF hazard assessment and future research.

2. Current State of Research

This chapter reviews the current state of research on sediment entrainment in GLOF-related mass flows. First, it introduces the fundamental characteristics and classification of GLOFs. Next, it provides an overview of typical trigger mechanisms and process chains. The chapter then focuses on sediment entrainment processes, their controlling factors, and their effects on flow behaviour. Finally, it discusses the implications for hazard assessment, highlighting existing knowledge gaps that motivate the empirical analyses presented in Chapter 5.

2.1. GLOFs: Definition and Classification

GLOFs are sudden and often catastrophic flood events resulting from the sudden release of water from lakes dammed by ice, moraine, or bedrock in glaciated terrain. These lakes typically form in depressions near or within glacier margins, where meltwater is impounded by natural dams composed of unconsolidated moraine material, glacier ice, or a combination of both (Bendle, 2025). Ongoing climate warming accelerates glacier retreat and permafrost degradation, processes that strongly influence the number, size, and stability of glacial lakes worldwide (Ahmed et al. 2022). As a consequence, the potential occurrence and characteristics of GLOFs are changing in many high-mountain regions (Compagno et al. 2022). In this study, GLOFs are understood not merely as hydrological flood releases, but as potential initiators of cascading mass flows whose downstream evolution is strongly controlled by sediment entrainment.

Figure 2.1 illustrates the formation and evolution of different types of glacial lakes and highlights associated failure mechanisms (Compagno et al. 2022). Common lake types include:

- **Supraglacial lakes**, which form directly on glacier surfaces and are typically highly dynamic and short-lived;
- **Ice-dammed lakes**, which develop where glacier ice obstructs valleys or depressions; and
- **Moraine-dammed (proglacial) lakes**, impounded behind unconsolidated moraine deposits left by retreating glaciers.

In addition to these surface-visible lake types, subglacial lakes may occur beneath glaciers. Although they are difficult to detect, their drainage can also generate outburst floods and complicate hazard assessment (Zhang et al. 2024). Among all lake types, moraine-dammed lakes are the most prevalent and pose particularly high hazard potential due to the weakly consolidated nature of morainic material and its susceptibility to erosion (Richardson & Reynolds, 2000b).

The stability and failure behaviour of glacial lakes depend on dam composition, internal drainage evolution, and external forcing such as temperature and precipitation variability (Worni et al. 2014). Understanding GLOF hazards therefore requires not only lake classification but also a process-based perspective on how instability evolves into catastrophic dam failure and downstream flooding.

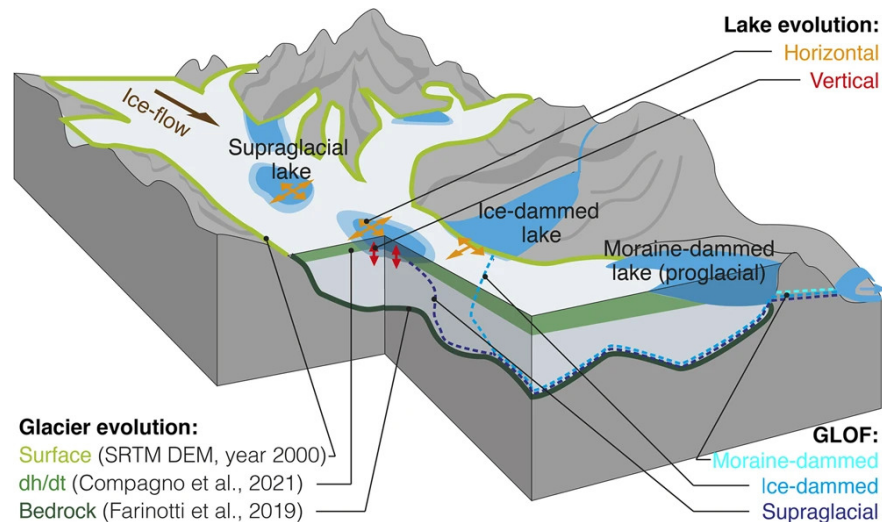


Figure 2.1.: Schematic representation of various glacial lakes and how they develop, as well as the different types of potential GLOF (Compagno et al. 2022)

2.2. Triggers and Processes

GLOFs result from complex process chains that link lake destabilisation, dam failure, and downstream flood propagation. A process-based understanding of these chains provides the foundation for analysing sediment entrainment and flow transformation during GLOF events. A process chain refers to the sequential coupling of geomorphic processes, in which one process triggers or amplifies subsequent processes along a spatial pathway (Mani et al. 2023).

2.2.1. Process Chain and Outburst Evolution

The evolution of a GLOF typically follows a sequence of interconnected physical and geomorphological processes that begin with a triggering disturbance and culminate in downstream mass-flow propagation. These stages are particularly relevant for understanding when and where sediment entrainment occurs along the flow path (Worni et al. 2014).

Figure 2.2 summarises the key stages of a typical GLOF process chain (Worni et al. 2014):

1. **Trigger event:** A sudden disturbance, such as a rockfall, ice avalanche, debris flow, or seismic shaking, impacts the lake.
2. **Wave generation and propagation:** An impulse wave travels across the lake surface, increasing in height and energy.
3. **Dam over-topping and stress:** The wave runs up the dam, potentially over-topping it and imposing strong mechanical stress.
4. **Dam erosion and breach:** Progressive erosion weakens the dam structure, often resulting in rapid breach formation.
5. **Flood wave release:** Rapid lake drainage generates a high-energy flood wave.
6. **Downstream propagation:** The flood wave travels downstream, interacting with valley morphology and entraining sediment.

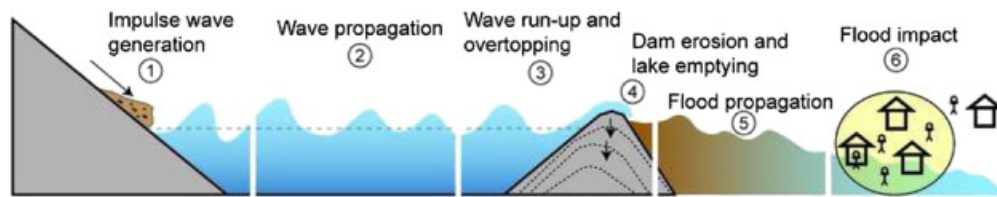


Figure 2.2.: Schematic representation of GLOF triggering mechanisms and their downstream effects (Worni et al. 2014)

The intensity and sequence of these stages depend on lake volume and depth, dam material properties, and the characteristics of the triggering event (Heller & Hager, 2011; Worni et al. 2014). While the initial stages control flood magnitude at the source, downstream processes largely determine flow transformation and hazard potential.

2.2.2. Triggering Mechanisms

GLOFs may be initiated by a variety of short-term and long-term triggering mechanisms that destabilise the lake dam. Short-term triggers are typically sudden, high-energy mass-movement events, whereas long-term processes gradually weaken dam structures and increase their susceptibility to failure (Emmer & Cochachin, 2013).

Short-term triggers are typically sudden, high-energy events that directly affect the stability of the lake dam. Common examples include ice or rock avalanches entering the lake and generating displacement waves capable of over-topping the dam and causing erosion (Heller & Hager, 2011). Intense precipitation events, such as cloudbursts or rapid snowmelt, can quickly raise the lake level, thereby increasing hydrostatic pressure and the risk of over-topping. Similarly, debris flows from adjacent slopes and ice calving from nearby glaciers can generate surges that put stress on the dam structure. Seismic activity, such as earthquakes, is another important trigger because it can weaken moraine dams through ground shaking or initiate mass movements into the lake (Emmer & Cochachin, 2013).

In contrast, long-term destabilisation triggers act more gradually, yet are crucial in making dams susceptible to failure. One key process is the melting of buried ice cores within moraine dams, which leads to the formation of voids and a loss of structural cohesion (Richardson & Reynolds, 2000a). Another process is seepage and piping, whereby water infiltrates the dam and gradually enlarges internal channels through erosion, thereby weakening its integrity (Kattelmann, 2003). These long-term processes are often exacerbated by short-term mass movement events that increase pore-water pressure and impose additional stress on weakened dam structures (Emmer & Cochachin, 2013).

Although triggering mechanisms determine the probability and initial magnitude of a GLOF, they do not explain the downstream evolution of GLOF flows. Once a dam breaches, the released flood rapidly interacts with the valley system, where erosion, bank failure, and sediment mobilisation strongly influence flow behaviour (Carrivick & Tweed, 2016; Walder & O'Connor, 1997). In steep, sediment-rich catchments, this interaction frequently leads to rapid transformation from a water-dominated flood into hyper-concentrated or debris-flow-like mass movements (Huggel et al. 2004; Iverson, 1997).

Therefore, understanding sediment entrainment is essential for explaining the evolution, magnitude, and spatial variability of GLOF-related mass flows. The following section reviews sediment entrainment processes and their controlling factors.

2.3. Sediment Entrainment in GLOF-Related Mass Flows

This section provides an overview of sediment entrainment processes in GLOF-related mass flows, including fundamental definitions, dominant mechanisms, controlling factors, and their spatial variability along the flow path.

2.3.1. Process Understanding and Definitions

Sediment entrainment is the process by which loose material, such as sand, gravel, moraine or slope debris, is mobilised from the riverbed, riverbanks or adjacent slopes, and becomes part of a flowing mass. During GLOFs, sediment entrainment is a key mechanism driving the transformation of water-dominated flood waves into hyper-concentrated flows or debris flows (Erokhin et al. 2018; Petrakov et al. 2020). In this study, sediment entrainment refers specifically to the incorporation of bed, bank and hillslope material into a flowing mass along the downstream propagation of a GLOF.

Sediment mobilisation is primarily influenced by the hydraulic shear stress exerted by the flow. Once critical thresholds are exceeded, erosion of the material occurs (Narama et al. 2018). In steep, narrow valleys, such as those found in the Tien Shan and Pamir regions, intense erosion and rapid sediment uptake may occur shortly after a dam breach (Shahgedanova et al. 2024). This favours the formation of highly dynamic debris flows whose composition and behaviour continue to change downstream, depending on the availability of materials and the slope gradient (Zaginaev et al. 2019).

Sediment entrainment processes can be conceptually grouped into two dominant mechanisms:

- **Surface entrainment:** Progressive erosion of channel beds and banks by hydraulic shear stress, resulting in bed scour, bank trimming, and sediment transport. This mechanism typically dominates in fluvial sections with gentler slopes (Narama et al. 2018; Rickenmann, 1999).
- **Mass entrainment:** Rapid mobilisation of sediment through slope failures, including debris flows, block falls, and collapses of moraine deposits, triggered by undercutting, saturation, or thermo-erosional weakening. This mechanism is particularly important in steep, weakly consolidated valley settings (Brüniger, 2023; Erokhin et al. 2018).

In reality, both mechanisms often co-occur, but their dominance shifts with confinement, slope, and sediment connectivity.

Figure 2.3 illustrates how riverbank slope steepness and lateral erosion intensity control the dominance of surface erosion versus mass-failure processes during flood events (Tomczyk et al. 2020). The relative importance of these mechanisms varies spatially and depends on hydrological forcing and local geomorphological conditions (Zaginaev et al. 2019).

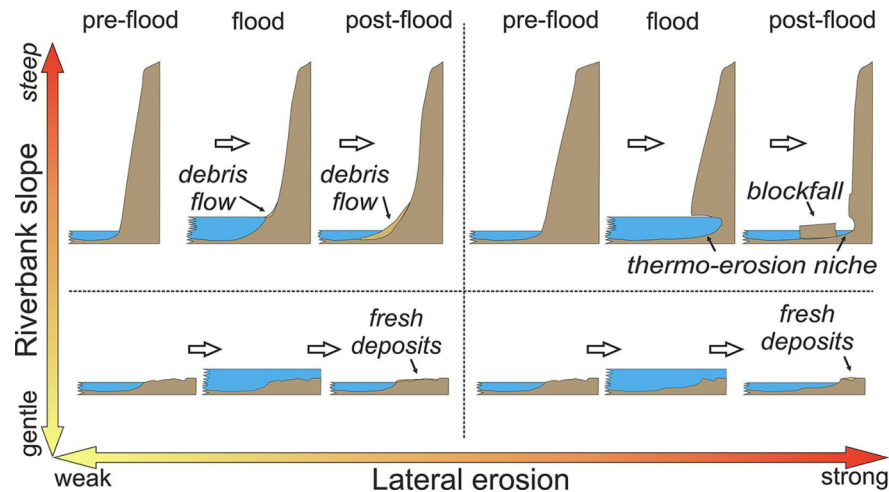


Figure 2.3.: Conceptual model of riverbank erosion illustrating dominant sediment entrainment processes under varying combinations of riverbank slope steepness and lateral erosion intensity. The schematic differentiates between surface entrainment and mass entrainment mechanisms, including debris flows, block falls and thermo-erosional undercutting during flood events. Source: (Tomczyk et al. 2020)

These mechanisms describe how sediment is mobilised. However, their relative importance depends strongly on a range of environmental and flow-related conditions, which are addressed in the following section.

2.3.2. Controlling Factors

The amount and spatial distribution of sediment entrainment during GLOFs is determined by a variety of factors, including hydrological, topographical, sedimentological, and vegetation-related factors. These factors determine the flow's erosion capacity and influence the likelihood of a transition to debris flows.

Hydrological factors: Flow velocity and discharge volume are the two main hydrodynamic drivers of entrainment (Hung et al. 2005; Iverson, 1997). High-velocity flows exert increased shear stress on the riverbed and valley slopes, mobilising loose sediment and debris. The steep rising limb of a GLOF hydrograph, which is often observed shortly after a dam breach, intensifies this effect (Janský et al. 2009; Worni et al. 2014). Higher discharge volumes also increase flow depth and transport capacity, enabling larger particle sizes and greater quantities of sediment to be incorporated (Zhou et al. 2024).

Geomorphometric factors: The morphology of a valley significantly influences the dynamics of hydrological processes and the mobilisation of sediments. Steep valley sections accelerate flow velocity, increasing the intensity of erosion in the upper reaches (Ahmed et al. 2022; Sidle et al. 2023). Narrow, deeply incised valleys concentrate flow energy, which can lead to hydraulic jumps and flow separations, resulting in increased local erosion (Allen et al. 2016; Zaginaev et al. 2019). In flatter valley areas, however, flow energy decreases, promoting sediment deposition and reducing the entrainment capacity in downstream sections (Ahmed, 2025).

Sedimentological factors: The nature and availability of loose material along the flow path play a decisive role in entrainment dynamics. Glacial loose sediments, moraine material and unstable slopes have a high mobilisation potential, particularly when sediment is saturated or

near-saturated (Sidle et al. 2023; Zaginaev et al. 2019). In permafrost areas, saturated or partially thawed soils become more erodible due to reduced shear strength and decreasing cohesion (Ahmed, 2025; Allen et al. 2016). Additionally, landslides or bank failures caused by deep erosion can release significant quantities of sediment into flowing water (Ahmed et al. 2022; Sidle et al. 2023).

Vegetation influence: Vegetation influences the release of sediment both directly and indirectly. Root systems stabilise soil and reduce surface erosion, particularly on gentle slopes (Emmer, 2017). Additionally, vegetation cover acts as a physical barrier, retaining sediment and reducing flow velocity (Westoby et al. 2014a). However, intense GLOFs can destroy vegetation over large areas, introducing organic material into the river and reducing surface roughness and erosion protection in affected regions (Cook et al. 2018). Deforested or sparsely vegetated areas are therefore significantly more susceptible to large-scale sediment release during such events (Sattar et al. 2022; Zhang et al. 2024).

In summary, these controlling factors do not act in isolation; rather, they vary in their influence along the flow path. The intensity and type of sediment uptake depend on the local combination of hydrodynamic conditions, valley geometry, and sediment availability. This spatial variability results in distinct entrainment patterns that are described systematically along the GLOF flow path in the following section.

2.3.3. Effects of Sediment Entrainment on Flow Behaviour

Sediment entrainment significantly alters the physical properties and flow behaviour of GLOFs. As sediments are incorporated into the moving mass of water, its density, viscosity and overall volume increase. These changes can lead to a hydraulic transformation of an initially water-dominated flood into a hyper-concentrated flow, or even a debris flow in extreme cases (Erokhin et al. 2018; Mergili, Schneider, et al. 2011). These flow types differ in their sediment concentration and internal structure. Hyper-concentrated flows are characterised by elevated but still fluid-dominated sediment concentrations, typically maintaining turbulent flow behaviour, whereas debris flows contain a substantially higher solid fraction and are often grain-supported, exhibiting viscoplastic behaviour (Iverson, 1997; Takahashi, 2007). The transition between these flow types is gradual and depends on sediment availability, entrainment intensity, and channel confinement. This transformation is associated with several key effects:

Increased destructive potential: Higher sediment concentrations lead to increased flow density and impact forces. This enhances the river's ability to erode riverbeds, damage infrastructure, and transport large boulders (Iverson, 1997). The presence of coarse material increases mechanical abrasion further and, through momentum transfer, increases the river's mobility (Berger et al. 2011; Takahashi, 2007). The resulting floods can reach catastrophic proportions, particularly in alpine or deforested regions where there is a high availability of sediment (Rickenmann, 1999).

Extended runout distances: Sediment-rich flows often have significantly greater ranges than floods of clear water. Their higher mass and internal cohesion enable them to maintain their kinetic energy over greater distances, particularly on moderate or gentle slopes (Haas, 2023; Sattar et al. 2022). These properties enable them to have a serious impact far beyond the area of the glacial lake itself, reaching distant valley areas (Dubey & Goyal, 2020; Worni et al. 2014).

Reduced flow velocity and pulsing behaviour: Although GLOFs can travel over long distances, sediment enrichment can reduce mean flow velocity through increased friction and viscosity, although locally high velocities may persist in steep confined reaches. (Kääb et al. 2005). However, instabilities often occur during such events, for example due to secondary entrainment or temporary blockages, leading to pulsating flow dynamics (Harrison et al. 2018). These irregular wave fronts can cause damage at multiple locations along the river's course, varying spatially and temporally (Narama et al. 2018).

Channel morphology alteration: The interaction of sediment-rich GLOF flows with the valley floor can cause significant geomorphological changes. These processes include deep erosion of the valley floor (incision), lateral erosion of slopes and flooding accompanied by sediment deposition. These geomorphic dynamics, in turn, promote the formation of secondary hazards, such as riverbed elevation (aggradation), unstable sediment dams, and the accumulation of potentially mobile sediment bodies (Zaginaev et al. 2019). In the high mountains of Central Asia in particular, repeated GLOF and debris flow events have been shown to influence long-term valley development (Pavlis et al. 1997).

These effects emphasise the importance of understanding sediment entrainment as both a local erosional process and a key driver of GLOF evolution and hazard amplification. Accurate prediction of these changes is crucial for assessing downstream risk and designing effective mitigation measures.

2.3.4. Spatial Differentiation of Entrainment Processes along the Flow Path

Sediment entrainment during GLOF-related mass flows shows significant spatial variation along the flow path (Mani et al. 2023; Zaginaev et al. 2016). This variation reflects systematic changes in flow energy, valley morphology, and sediment availability. These spatially differentiated entrainment and remobilisation processes are characteristic of geomorphic process chains in high-mountain regions. This is particularly evident when fluvial coupling increases sediment mobilisation downstream (Mani et al. 2023). Reconstructions of glacial lake outburst floods in the northern Tien Shan demonstrate that sediment uptake and deposition vary systematically along the flow path. There is pronounced erosion in the upper reaches and progressive deposition in the downstream valley sections (Zaginaev et al. 2016). In this study, the flow path is conceptually divided into three zones: an initial zone, a transit zone, and a deposition zone. Figure 2.4 illustrates this zonation and the associated transformation of flow processes along a typical GLOF flow path (Meyrat et al. 2024). For analytical purposes, the flow path is conceptually subdivided into three functional process zones.

The initial zone, located immediately downstream of the lake breach, is characterised by extremely high flow velocities and shear stresses. Steep slopes and confined channels promote intense basal erosion and the rapid mobilisation of unconsolidated moraine and fluvial sediments. In this zone, sediment entrainment is usually dominated by surface erosion. The transformation from a water flood to a mud flood may occur over short distances if there is enough loose material available (Erokhin et al. 2018; Petrakov et al. 2020; Zaginaev et al. 2019).

The transit zone includes the main downstream transfer section, where the flow's energy level remains high but is increasingly affected by local geomorphological conditions. Alternating channel constrictions and valley widenings control spatial variations in erosive power (Mergili, Schneider, et al. 2011; Sidle et al. 2023). Narrow sections experience increased erosive power due to enhanced flow confinement, while wider sections favor temporary deposition, followed by re-entrainment,

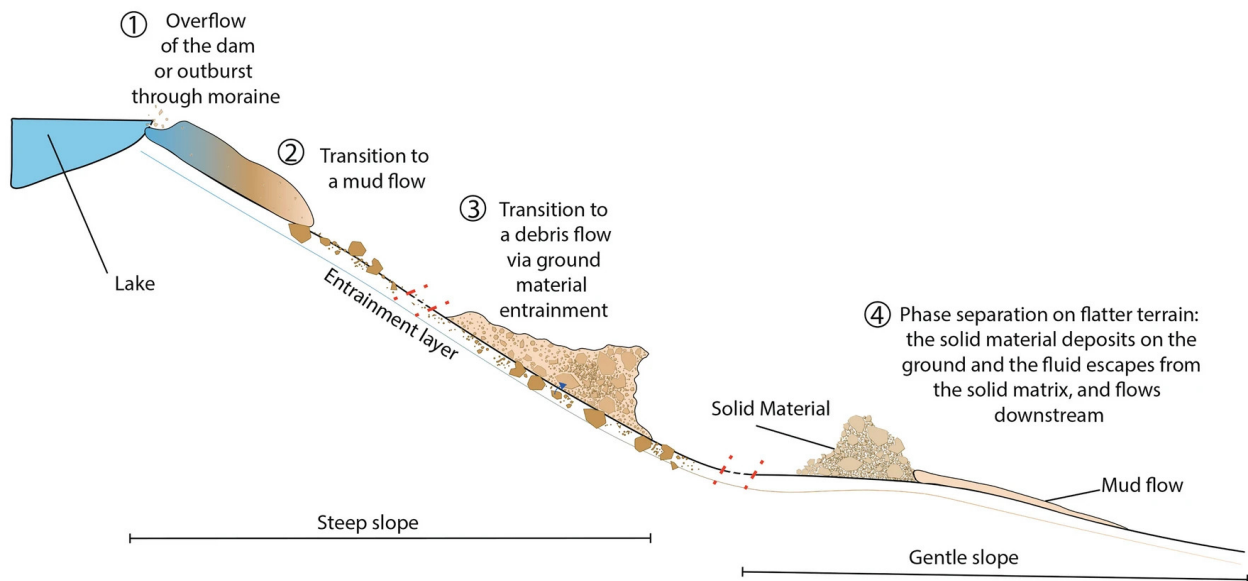


Figure 2.4.: Conceptual illustration of process evolution and sediment entrainment along a GLOF flow path. The schematic shows the transition from an initial water flood released by dam overtopping or moraine breach, to a mud flow and subsequently to a debris flow through progressive sediment entrainment on steep slopes. On gentler terrain, decreasing flow energy leads to phase separation and sediment deposition. Source: (Meyrat et al. 2024)

during subsequent surges (Mergili, Schneider, et al. 2011; Sidle et al. 2023). However, additional sediment is supplied by processes such as bank collapse, slope failure, and the remobilisation of older deposits (Sidle et al. 2023).

In the deposition zone, decreasing slopes and widening valley floors lead to reduced flow energy and transport capacity. Deposition processes dominate, leading to the accumulation of coarse debris and fine sediments in channel beds and overbank areas. However, sediment-rich flows can still locally erode banks or mobilise previously deposited material, especially during pulsed flow phases or in confined channel segments (Zaginaev et al. 2019). The size of this zone depends on flow rheology, sediment concentration, and the morphology of the downstream valley (Rickenmann, 1999; Shahgedanova et al. 2024).

The zones are conceptual and may overlap, but they provide a useful template for comparing entrainment patterns between catchments. During GLOFs, sediment entrainment is governed by spatially variable processes along the entire flow path rather than by conditions at the lake alone. Recognizing these process zones is therefore essential for interpreting differences in sediment mobilisation and improving process-based GLOF hazard assessments. The methodological framework presented in the following chapter is motivated by the need to capture these interacting processes.

2.4. Implications for Hazard Assessment and Research Gaps

The literature demonstrates that sediment entrainment controls the magnitude and impact of GLOF-related mass flows but remains difficult to quantify due to limited field data and strong spatial variability. In the context of this thesis, hazard refers to the physical process and its potential magnitude, independent of exposure and vulnerability, which together define risk.

Many hazard assessments continue to rely primarily on hydrological indicators, neglecting or oversimplifying the role of geomorphometric controls and sediment availability along the flow path. This results in substantial uncertainty in estimates of mobilised sediment volumes and downstream impacts.

These limitations highlight the importance of adopting an integrated, empirical approach that combines hydrological analyses, geomorphometric terrain assessments and documented event data. It is particularly important to address these gaps in regions such as the Ile-Alatau, where GLOFs are recurrent yet process-based studies are scarce. The following chapters provide an empirical analysis of the influence of hydrology and geomorphometry on sediment entrainment at the catchment scale.

3. Study Area and Regional Context

This chapter introduces the study area in the Ile-Alatau mountain range and provides the regional context for analysing sediment entrainment during GLOFs. It outlines the geographical setting, glaciological and climatic conditions, geomorphological characteristics, and the regional hazard context. Together, these factors define the boundary conditions controlling sediment availability, flow intensity, and entrainment efficiency in GLOF-related cascading mass flows.

3.1. Regional Setting and Catchment Overview of the Ile-Alatau

The Ile-Alatau mountain range is located in southeastern Kazakhstan and forms the northernmost range of the Tien Shan mountain system. It extends approximately 190 km in an east–west direction along 43° N, from 76°05′ E to 78°20′ E, and spans about 30 km in a north–south direction, bordering the city of Almaty to the north. (Medeu et al. 2020). Located between the high mountains of the Tien Shan and the adjacent Kazakh steppe, the range exhibits pronounced vertical gradients in climate, hydrology, and geomorphological processes. Elevations range from approximately 600 m a.s.l. in the foreland to more than 4,900 m a.s.l. at the highest peaks, with Talgar Peak reaching 4,979 m a.s.l. (Medeu et al. 2020).

The study area comprises several steep alpine catchments that drain northwards from the main ridge of the Ile-Alatau towards the densely populated foothills and the city of Almaty. An overview of the catchments considered is shown in Figure 3.1. From west to east, these include Uzynkargaly, Chamalgan, Kaskelen, Aksai, Kargaly, Ulken Almaty, Kishi Almaty, Talgar, Issyk, and Turgen. These catchments are characterised by short longitudinal distances between glacierised headwaters and downstream valley floors, typically ranging from 5 to 15 km. This strong topographic coupling promotes rapid hydrological response and efficient transfer of water and sediment during high-magnitude events (Rickenmann et al. 2024; Stepanov & Yafyazova, 2014).

Despite differences in catchment size, topography, and degree of glaciation, the analysed catchments share a broadly similar geomorphological setting. Headwater areas are dominated by cirque and valley glaciers, extensive moraine complexes, and steep rock walls, whereas middle and lower reaches consist of deeply incised valleys with locally widening valley floors. Several catchments contain documented glacial lakes or have experienced historical GLOFs, providing a suitable basis for comparative, catchment-scale analyses of sediment entrainment processes (Medeu et al. 2020; Mussina et al. 2024). The empirical analyses presented in subsequent chapters focus on a subset of these catchments with documented GLOF activity and sufficient data availability.

The compact spatial extent of the Ile-Alatau, combined with its pronounced relief and short hydrological response times, creates highly dynamic mountain catchments. Steep channel gradients, limited storage capacity in valley floors, and the close spatial coupling between glacierised headwaters and downstream settlements favour rapid runoff concentration and efficient sediment transfer during extreme events. In addition, ongoing glacial retreat and paraglacial adjustment processes continuously modify sediment availability and slope stability in the headwater regions. This combination of high relief energy, active geomorphic processes, and exposed downstream

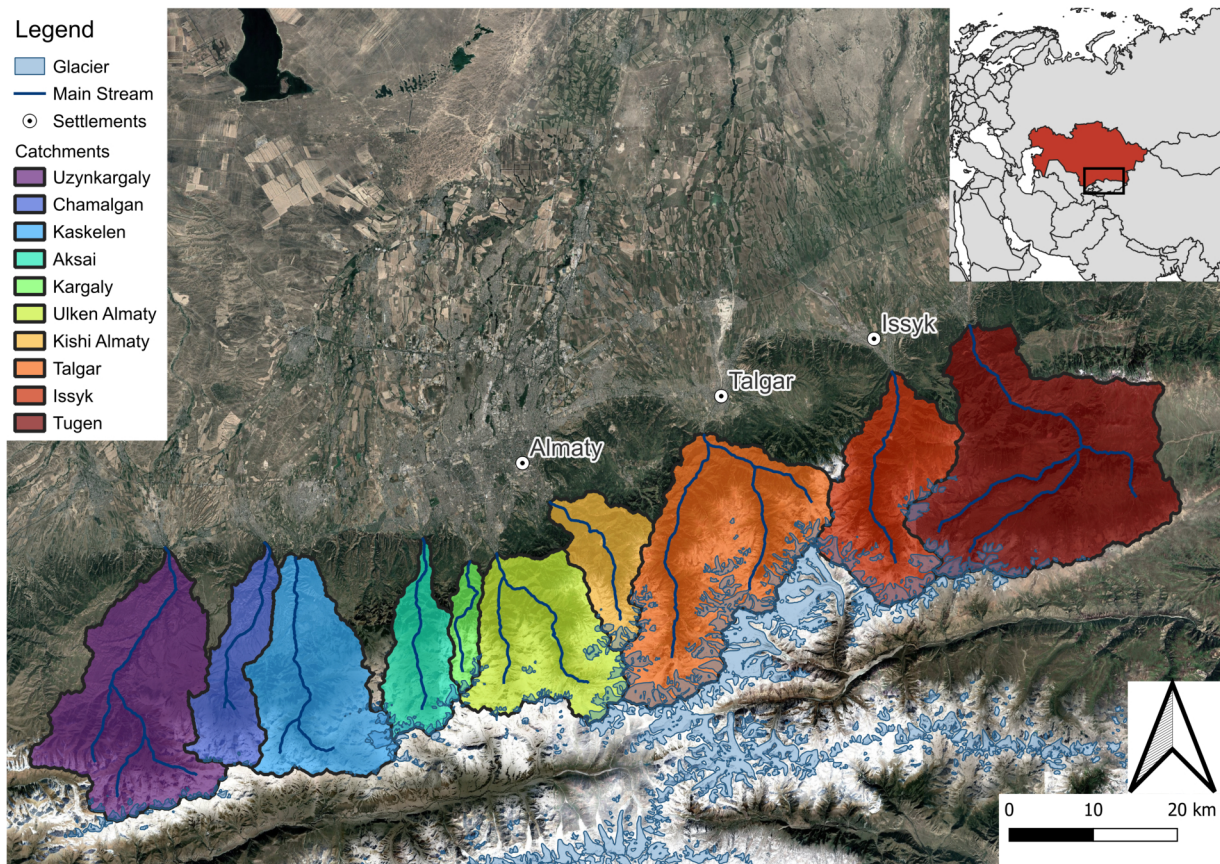


Figure 3.1.: Overview of the major catchments in the Ile-Alatau Mountains, southeastern Kazakhstan. Delineated catchment boundaries, their respective main streams, and glacier extents are displayed on satellite imagery, with major settlements indicated for spatial reference. The inset map shows the location of the study area within Central Asia. Country boundaries in the inset are based on vector data from Natural Earth (1:110 million scale). Data sources: satellite imagery © Google Earth; glacier outlines: RGI Consortium (2023); country boundaries: Natural Earth (2026).

infrastructure makes the Ile-Alatau particularly well suited for investigating sediment entrainment in GLOF-related cascading mass flows.

3.2. Glaciological and Climatic Conditions

Glaciation in the Ile-Alatau region is largely confined to elevations above approximately 3,200–3,400 m a.s.l., where cirque and valley glaciers occupy north-facing slopes and high-altitude basins. The highest concentration of glacier area occurs between 3,500 and 4,200 m a.s.l., while glacier tongues typically descend to elevations of 3,000–3,200 m a.s.l. (Iskaliyeva et al. 2025). Over recent decades, glaciers throughout the region have experienced pronounced retreat and thinning, resulting in substantial reductions in glacier area and volume across most catchments (Chigrinets et al. 2020).

Glacier retreat has led to the widespread formation and expansion of glacial lakes in recently deglaciated areas. An inventory of glacial-moraine lakes on the northern slope of the Ile-Alatau documents an increase in lake numbers from approximately 20 in 1978 to 77 in 2021 (Mussina et al. 2024). Most lakes are proglacial and dammed by weakly consolidated, locally ice-cored

moraines, making them particularly susceptible to failure. Individual lake volumes commonly reach 10^5 – 10^6 m³, sufficient to generate high-magnitude GLOFs upon sudden drainage (Medeu et al. 2020).

The regional climate of the Ile-Alatau is continental, characterised by strong seasonal contrasts and pronounced elevation-dependent temperature gradients. Mean annual air temperatures range from approximately +8 to +10 °C in the foreland near Almaty to below –6 °C in the high mountain zone above 4,000 m a.s.l. (Sorg et al. 2012). At elevations relevant for glacier melt and glacial lake development (approximately 3,200–4,000 m a.s.l.), mean summer temperatures frequently exceed 0 °C for several months, favouring sustained glacier ablation (Chigrinets et al. 2020).

Seasonal temperature and precipitation patterns for the northern Ile-Alatau are illustrated in Figure 3.2, which shows mean monthly air temperature and precipitation at the Almaty meteorological station for the period 1991–2020. Although located at lower elevations, the station provides a representative reference for regional climatic seasonality. While absolute values differ at higher elevations, the station captures the seasonal timing of temperature and precipitation that governs melt-season discharge and lake filling. The data indicate cold winters, warm summers, and a pronounced precipitation maximum in spring and early summer, driven by large-scale circulation patterns and orographic enhancement (Mussina et al. 2024; Sorg et al. 2012). This seasonal regime strongly influences snowmelt, runoff generation, glacier ablation, and glacial lake filling, thereby affecting the timing and magnitude of potential GLOFs (Iskaliyeva et al. 2025).

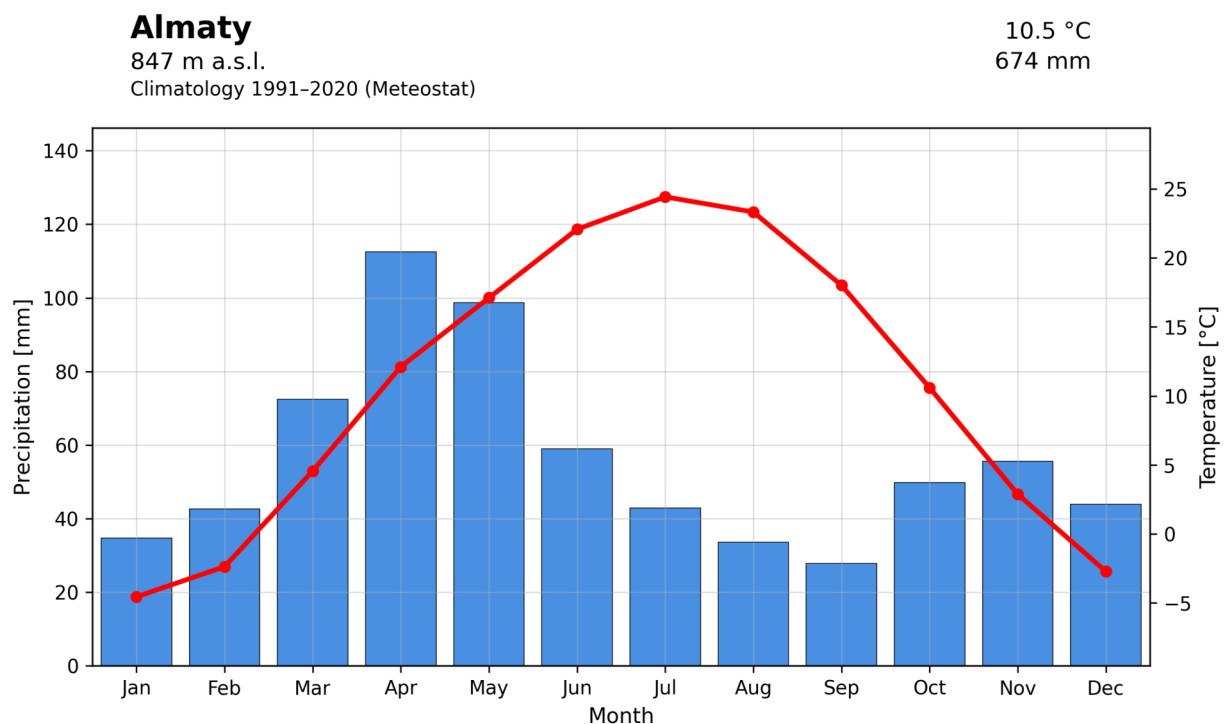


Figure 3.2.: This climate diagram shows the mean monthly air temperature (red line with markers) and monthly precipitation (blue bars) for the Almaty meteorological station (847 m a.s.l.) for the climatological reference period of 1991–2020. The diagram illustrates the pronounced seasonal temperature contrast and spring-to-early summer precipitation maximum characteristic of the northern Ile-Alatau region. The climate data were obtained from the Meteostat database (Meteostat, 2025).

Annual precipitation increases markedly with elevation, from approximately 500–600 mm yr⁻¹ in the foothills to 800–1,000 mm yr⁻¹ or more in the high mountain zone, where a substantial fraction falls as snow (Iskalyeva et al. 2025). The resulting nival–glacial hydrological regime is characterised by peak discharges during the summer melt season (June to August). Superimposed intense rainfall events can further amplify discharge peaks, promote rapid glacial lake filling, and destabilise moraine dams, thereby increasing the likelihood of GLOF initiation (Chigrinets et al. 2020; Iskalyeva et al. 2025).

Together, these glaciological and climatic conditions favour high-magnitude, short-duration flood events during the summer season. In combination with abundant unconsolidated sediment along steep valley floors, such events facilitate extensive sediment entrainment along GLOF flow paths.

3.3. Geomorphological Settings

The geomorphological characteristics of the Ile-Alatau exert a primary control on sediment availability and entrainment efficiency during extreme flood events. Steep topography, confined valley morphologies, and extensive paraglacial sediment stores create favourable conditions for both surface erosion and mass entrainment along GLOF flow paths.

3.3.1. Topography and Valley Morphology

The region is characterised by extreme relief, including rugged, high mountain ranges and steep slopes, as well as high geomorphological activity. In the upper catchment areas, valley gradients often exceed 20–30°, promoting high flow velocities and intense erosive forces during flood events (Lyy et al. 2025). Narrow, deeply incised valleys, particularly in the transition zone from glaciated headwaters to medium altitudes, favour the concentration of rivers and exert high shear stresses on riverbeds and riverbanks (Stepanov & Yafyazova, 2014). These features increase the region's susceptibility to debris flows and outburst floods from glacial moraine lakes (Mussina et al. 2023, 2024). Therefore, the interaction between geomorphological processes, slope gradients and hydrological dynamics is a key element in natural hazard management in this region (Lyy et al. 2025; Mussina et al. 2023, 2024).

3.3.2. Sediment Storage and Paraglacial Deposits

Sediment availability in the Ile-Alatau is high due to the widespread presence of unconsolidated glacial and paraglacial deposits. These include lateral and terminal moraines, talus slopes, debris cones, and glaciofluvial sediments stored along valley floors. Many of these deposits are poorly consolidated and highly susceptible to erosion, especially when saturated or undercut by high-energy flows (Mussina et al. 2023; Rickenmann et al. 2024).

Additionally, permafrost degradation at high elevations and freeze-thaw processes on steep rock walls result in a continuous supply of sediment through rockfall and shallow slope failures. In the middle and lower reaches, older alluvial and debris-flow deposits provide additional sources of remobilisable material. The combination of steep topography and abundant sediment strongly favours surface erosion and mass entrainment during extreme hydrological events (Stepanov & Yafyazova, 2014).

3.3.3. Geological and Lithological Setting

The Ile-Alatau mountain range is predominantly composed of crystalline and metamorphic rocks, such as granite, gneiss and schist, with minor sedimentary rock formations present at lower elevations (Bolch et al. 2011). Its geological structure is characterised by strong tectonic fragmentation, resulting in a high density of fissures and faults. These lithological characteristics favour intense mechanical weathering, particularly under periglacial conditions (Shahgedanova et al. 2024). Studies in the region demonstrate that frost weathering and slope instability, caused by the fractured geology, play a pivotal role in the release of materials (Mussina et al. 2023).

As a result, the bedrock breakdown and frost-induced disintegration produce large quantities of coarse-grained, poorly consolidated debris that can easily be transported into slopes, moraines and valley floors. These processes are significantly enhanced by paraglacial reorganisation following glacier retreat, resulting in an exceptionally high concentration of loose material along potential GLOF flow paths (Bolch et al. 2011; Nurakynov et al. 2025). The low cohesion and heterogeneous grain size distribution of these deposits significantly reduce the critical shear stress required for erosion to occur, facilitating sediment uptake and enabling rapid flow transformations during outburst events (Shahgedanova et al. 2024). Modelling of the region has shown that low resistance forces in sediment bodies can trigger large-scale erosion dynamics even with moderate runoff (Mussina et al. 2025).

3.4. Debris-Flow Activity and Hazard Context

The Ile-Alatau mountain range in Kazakhstan is considered the most debris-flow-prone in the country and has a long history of damaging mass-movement events. Since the beginning of the 20th century, historical records have documented several hundred debris flows, with rain-induced and glacially triggered events being the dominant process types (Medeu et al. 2019, 2020).

GLOFs occur less frequently than rain-induced events in the Ile-Alatau mountain range, but they are typically characterised by larger volumes and a higher destructive potential. Several of the most severe events documented in this region were triggered by outbursts of moraine-dammed lakes or sudden releases of subglacial or englacial water (Shahgedanova et al. 2024). Due to the steep longitudinal profiles of the catchments and the widespread availability of unconsolidated glacial and periglacial sediments, these flood waves commonly undergo a rapid transformation into debris-rich flows within short downstream distances (Popov et al. 2024; Stepanov & Yafyazova, 2014). These processes pose a serious threat to infrastructure, settlements and tourist activities in the Alpine valleys of the northern Tien Shan region (Kapitsa et al. 2023).

The proximity of glaciated headwaters to densely populated valleys in the Ile-Alatau Mountains significantly increases the danger posed by glacial debris flows. Numerous catchment areas have undergone transformations from flash floods to sediment-rich debris flows within a few kilometres, resulting in long run-out distances that can have a significant impact on the underlying infrastructure, including urban areas in and around Almaty (Medeu et al. 2019; Mussina et al. 2023). Catchments with steep gradients, extensive glacier coverage and significant volumes of potentially unstable moraine lakes are particularly vulnerable (Popov et al. 2024; Shahgedanova et al. 2024). These hazards necessitate continuous monitoring and specific protective measures, given that floods frequently transform into debris flows with substantial kinetic energy shortly after exiting the glacier area (Medeu et al. 2019; Popov et al. 2024).

3.5. Relevance of Regional Conditions for Sediment Entrainment

The regional characteristics of the Ile-Alatau create highly favourable conditions for efficient sediment entrainment during GLOF-related cascading mass flows. Steep and confined valley geometries, short distances between glacial source areas and downstream channels, and abundant unconsolidated sediment collectively facilitate rapid erosion, volumetric growth, and flow transformation. As shown in Table 3.1, all analysed catchments combine high relief, varying degrees of glaciation, and substantial sediment storage in channels, moraine complexes, and slope deposits. These interacting physiographic and geomorphological factors generate pronounced spatial variability in entrainment efficiency, which in turn strongly influences flow magnitude and downstream impact. Given the long history of glacially triggered floods and debris flows in the Ile-Alatau and the close proximity of source areas to inhabited valleys, even moderate differences in entrainment conditions can substantially alter hazard intensity. The dominant valley sediment stores were identified based on published geomorphological descriptions and qualitative interpretation of satellite imagery, while their quantitative contribution along reconstructed GLOF flow paths is assessed in Chapter 5. This regional synthesis provides the boundary conditions for the subsequent conceptual and empirical analyses and underlines the importance of catchment-scale approaches for process-based GLOF hazard assessment in south-eastern Kazakhstan. Accordingly, the empirical analysis tests how slope, channel confinement, contributing area, and mapped sediment stores jointly explain observed entrainment patterns along reconstructed GLOF flow paths.

Table 3.1.: Physiographic, cryospheric and geomorphological characteristics of the catchments selected for conceptual and empirical analysis in this study.

Catchment	Area [km ²]	Elevation range (min-max) [m a.s.l.]	Relief [m]	Glacierised Area [km ²]	Documented glacier lakes ¹	Dominant valley sediment stores	Historical GLOF activity
Kaskelen	296.5	1098-4235	3137	11.6	-	Predominantly channel-stored sediments; minor moraine and slope-derived inputs	documented
Kargaly	45.6	1385-4147	2762	2.4	-	Channel-stored sediments; minor moraine remnants	documented
Ulken Almaty	273.2	1249-4372	3123	31.5	21	Channel sediments and slope-derived deposits	documented
Kishi Almaty	124.9	1138-4353	3215	8.9	5	Significant slope-derived and moraine sediments	documented
Talgar	472.4	1159-4962	3803	84.2	29	Moraine complexes and channel deposits	documented
Issyk	266.6	1179-4623	3444	95.9	22	Mixed channel, moraine and floodplain deposits	documented

¹ Mussina et al. (2024)

4. Conceptual Framework for GLOF-Related Sediment Entrainment

This chapter develops a conceptual framework for sediment entrainment in GLOF-related cascading mass flows in Central Asia by synthesising documented case studies from the Ile-Alatau to identify recurring patterns, dominant controls, and key research gaps that inform the empirical analyses in Chapter 5.

4.1. Data Basis and Selection of GLOF Case Studies

This section outlines the empirical basis for developing the conceptual framework of sediment entrainment in GLOF-related cascading mass flows, as presented in this chapter. While the data introduced here are not used for quantitative analysis, they serve as qualitative evidence to identify recurring patterns of sediment mobilisation and synthesise dominant process controls along GLOF flow paths.

The conceptual framework is based on documented historical GLOF events in the Ile-Alatau Mountains. Through systematic comparison of these events, the aim is to identify common process characteristics and distinguish typical entrainment behaviours from event-specific anomalies. This approach enables the development of a generalised, process-oriented understanding of sediment entrainment under Central Asian high-mountain conditions.

4.1.1. Data Sources

The conceptual synthesis presented in this chapter is based on published documentation of historical GLOF events. This documentation provides qualitative descriptions of flow evolution, geomorphological setting, and sediment mobilisation processes.

One primary source is the comprehensive documentation of historical GLOFs in the Ile-Alatau Mountains by Medeu et al. (2016). These records contain detailed reconstructions of event sequences, downstream impacts, and geomorphological conditions along affected flow paths. While quantitative measurements of erosion volumes are limited, the descriptions enable the identification of zones of intense sediment entrainment, flow transformation, and deposition.

Established GLOF databases were consulted to supplement these descriptions, particularly the datasets compiled by Lützow et al. (2023) and Shrestha et al. (2023). These databases provide hydrological and volumetric parameters that contextualise the documented events. Where discrepancies occurred, information was cross-checked with additional regional studies.

Further insights into process characteristics and regional context were drawn from studies by Medeu et al. (2022), Popov et al. (2024, 2025), Rickenmann et al. (2024), and Yafyazova (2011). Together, these sources provide a consistent qualitative basis for interpreting sediment entrainment processes across multiple GLOF events. The conceptual framework developed in this chapter relies exclusively on these documented observations.

4.1.2. Selection Criteria and Representativeness

The selection of GLOF events was guided by the availability of sufficient documentation for a qualitative reconstruction of sediment entrainment processes along the flow path. Fifteen historical GLOF events from several catchments in the Ile-Alatau Mountains were included in the conceptual analysis.

These events span a wide range of magnitudes, geomorphological settings, and process chains that are characteristic of high-mountain catchments in Central Asia. Despite differences in lake size, triggering mechanisms, and downstream impacts, all of the events share key characteristics relevant to sediment entrainment. These characteristics include steep valley gradients, short catchment lengths, and abundant unconsolidated sediment.

Rather than aiming for statistical representativeness, the selection focuses on capturing typical process constellations that recur across multiple events. This allows us to identify and compare dominant entrainment mechanisms and controlling factors across contrasting catchments. This forms the basis for a generalised conceptual understanding of sediment entrainment in GLOF-related cascading mass flows.

4.1.3. Overview of Selected GLOF Events

The documented GLOF events are distributed across several north-draining catchments of the Ile-Alatau Mountains (see Figure 4.1). The affected catchments include Kaskelen, Kargaly, Ulken Almaty, Kishi Almaty, Talgar, and Issyk. Most of these events originated from moraine-dammed lakes in glacierised headwater areas where steep slopes and high sediment availability promote rapid propagation downstream and intense sediment entrainment.

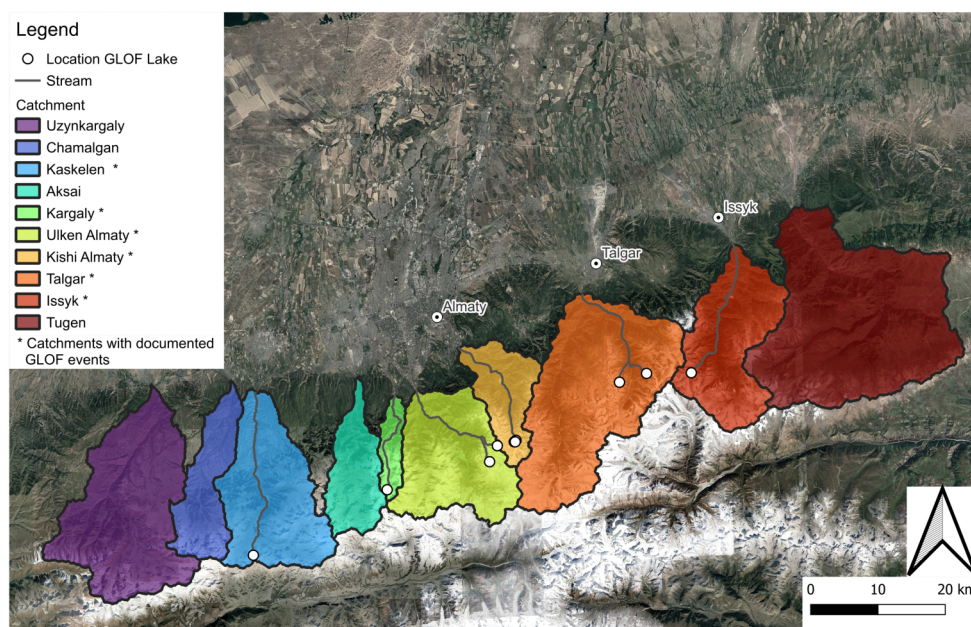


Figure 4.1.: Spatial distribution of glacial lakes and documented GLOF events in the Ile-Alatau Mountains (Northern Tien Shan, southeastern Kazakhstan). Coloured polygons show the major catchments in the study region. White circles indicate glacial lakes with recorded outburst events. Catchments marked with an asterisk (*) fulfilled the selection criteria and were included in the detailed analysis of this study.

Table 4.1 summarises selected events, listing the affected catchments, the associated glaciers and lakes, and the dates of the recorded outbursts. Several catchments have experienced repeated GLOF events originating from the same glacial lake, indicating persistent instability and recurring sediment mobilisation along the same flow paths. This recurrence provides valuable insight into the spatial consistency of entrainment processes and highlights the importance of catchment-scale controls.

Table 4.1.: Overview of documented GLOF events considered in this study, including lake type, outburst mechanism, documented triggering conditions, and references.

Catchment	Glacier	Lake	Dates of outburst	Lake Type	Outburst Mechanism	Documented GLOF Driver	References
Kaskelen	No. 25	No. 16	23.07.1980	Moraine dammed	Subglacial tunnel	glacier & snow melt over several years	1,3,4,5,9
Kaskelen	No. 25	No. 16	05.07.1986	Moraine dammed	Subglacial tunnel	glacier & snow melt over several years	1,3,5,9,10
Kargaly	Kargalinka	No. 1	23.07.2015	Moraine dammed	Subglacial tunnel	High temperatures	2,3,5,7,9,10,11
Kargaly	Kargalinka	No. 1	14.08.2019	Moraine dammed	Subglacial tunnel	artificial emptying	2,3,9,10
Ulken Almaty	Kumbel	No. 14	19.08.1975	Supraglacial	overtopping and Moraine collapse	high temperature ⇒ glacier melt	1,3,5,7,8,10
Ulken Almaty	Sovetov	No. 13	03.08.1977	Moraine dammed	Moraine collapse	high temperature ⇒ glacier melt	1,2,3,4,5,7,8,10
Kishi Almaty	Central Tuyksu	No. 2	20.08.1951	Moraine dammed	Subglacial tunnel	high temperature & moistening the moraine due to infiltration	1,2,3,5,7,9,10
Kishi Almaty	Central Tuyksu	No. 2	07.08.1956	Moraine dammed	Subglacial tunnel	high temperature ⇒ glacier & snow melt and rapid thawing of the soil in the upper moraine layer	3,5,10
Kishi Almaty	Central Tuyksu	No. 2, No. 3	15.07.1973	Moraine dammed	Subglacial tunnel	high temperatures & intense rainfall	1,2,3,4,5,7,8,9,10
Talgar	Spotivnyi	No. 7	21.06.1979	Moraine dammed	Subglacial tunnel	glacier & snow melt over several years	1,2,3,4,5,9,10
Talgar	Bezmyannyi	No. 8	06.07.1993	Moraine dammed	Subglacial tunnel	glacier & snow melt over several years	1,2,3,4,5,9,10
Talgar	Bezmyannyi	No. 8	17.07.2014	Moraine dammed	Subglacial tunnel	glacier & snow melt over several years	1,2,3,5,9,10
Issyk	Zharsay	No. 17	06.07.1958	Moraine dammed	Subglacial tunnel	precipitation, lake rupture, and a combination of these factors	5,7,9,10
Issyk	Zharsay	No. 17	07.07.1963	Moraine dammed	Subglacial tunnel	heavy warm rain and thunderstorms	1,3,5,6,7,8,9,10
Issyk	Zharsay	No. 17	03.07.1977	Moraine dammed	Subglacial tunnel	high temperature ⇒ glacier & snow melt	1,4,9,10

¹ Medeu et al. (2016)

⁴ Popov et al. (2024)

⁷ Yafyazova (2011)

¹⁰ Shrestha et al. (2023)

² Medeu et al. (2020)

⁵ Popov et al. (2025)

⁸ Rickenmann et al. (2024)

¹¹ NASA (2015)

³ Medeu et al. (2022)

⁶ Yafyazova (2007)

⁹ Lützwow et al. (2023)

A comprehensive compilation of all the GLOF events considered in this study is provided in Appendix A. Additionally, qualitative descriptions of flow evolution, sediment entrainment and downstream impacts are summarised for each event in Appendix A.2.

Together, these documented events form the conceptual foundation for identifying recurring patterns of sediment entrainment, which are systematically synthesised in the following sections of this chapter.

4.2. Documented Patterns of Sediment Entrainment

Building on the general mechanisms, controlling factors and spatial zonation of sediment entrainment outlined in Chapter 2, this section examines how these theoretical concepts are manifested along documented GLOF flow paths in the Ile-Alatau region. Instead of reiterating generic process descriptions, the focus is on identifying recurring empirical patterns of sediment mobilisation, spatial variability and flow transformation observed in historical events.

4.2.1. Magnitude of Sediment Entrainment

In the Ile-Alatau region, documented GLOF-related mass flows consistently demonstrate that the total volume of mobilised sediment often substantially exceeds the volume of water released during the initial lake outburst. In several well-documented cases, the volume of the debris flow is one to two orders of magnitude larger than the volume of the triggering water, which highlights the dominant role of downstream sediment entrainment rather than source-volume control alone (Medeu et al. 2016; Popov et al. 2025).

The Issyk catastrophe of 1963 is a particularly illustrative example. A glacial lake with an estimated volume of less than 500,000 m³ triggered a cascading debris flow with a total volume of approximately 5,800,000 m³. This disproportionate scaling indicates the extremely efficient entrainment of moraine deposits, talus material, and unconsolidated valley-fill sediments along the flow path (Medeu et al. 2016). Similar amplification effects occurred during the Tuyuksu events of 1956 and 1973. Relatively modest water releases resulted in debris flows exceeding several million cubic metres due to intense erosion and sediment uptake downstream (Popov et al. 2025).

In contrast, events initiated by subglacial or intramoraine drainage through stable tunnels or filtration pathways often exhibit significantly lower entrainment magnitudes. In these cases, erosion of the dam structure is limited, and sediment uptake is largely confined to channel bed and bank erosion. Consequently, the overall process remains supply-limited, and debris-flow volumes remain closer to the initial water volume. The 1958 Zharsay event exemplifies this behaviour, as early deposition on low-gradient valley sections restricted downstream entrainment (Yafyazova, 2011).

These observations suggest that sediment entrainment magnitude is primarily controlled by flow energy and discharge dynamics, sediment availability along the channel network, and the susceptibility of moraine and valley-fill deposits to erosion, rather than by the absolute lake volume. Consequently, small or moderate glacial lakes may trigger highly destructive mass flows if downstream conditions favour progressive sediment uptake (Popov et al. 2025). In contrast, larger lakes may result in comparatively moderate debris flows when entrainment potential is limited.

4.2.2. Spatial Distribution of Entrainment along the Flow Path

The spatial differentiation of sediment entrainment observed in the case studies that have been documented closely corresponds to the zonation of GLOF flow paths into the initial, transit and deposition zones that were introduced in subsection 2.3.4. This framework is useful for interpreting systematic changes in erosion, sediment uptake and deposition along the flow path.

Across the reviewed case studies, sediment entrainment follows a characteristic spatial pattern along the flow path. This pattern reflects systematic changes in slope, confinement, sediment availability, and flow regime. In the immediate source area, entrainment is often limited when lake

drainage occurs through subglacial tunnels or internal piping because these mechanisms restrict the direct erosion of the dam, producing an initially water-dominated outburst flood. In contrast, surface overflow or structural dam failure can lead to significant entrainment at the source, especially where ice-rich or loosely consolidated moraine material is exposed (Yafyazova, 2011).

The most intense and sustained sediment entrainment usually occurs in the upper to middle reaches of the watershed. These sections are characterised by steep channel gradients, narrow cross sections, and abundant unconsolidated sediments. These features create optimal conditions for deep channel incision and lateral erosion. Field observations from several Ile-Alatau events document incision depths ranging from several metres to over 30 or 40 metres within moraine deposits during extreme debris flows. This erosion supplies large volumes of sediment directly and destabilises adjacent slopes, triggering secondary landslides that further increase sediment availability (Medeu et al. 2016).

As the flow propagates downstream, entrainment rates generally decrease due to declining channel gradients and progressive energy dissipation. In the lower reaches, deposition becomes increasingly dominant, leading to the accumulation of large volumes of sediment on valley floors, alluvial fans, and in downstream lakes. However, the transition from erosion-dominated to deposition-dominated behaviour is not abrupt and depends strongly on event magnitude. In high-energy events, such as the 1963 Issyk debris flow, significant entrainment continues far downstream. This allows the flow to retain its destructive potential in lower-gradient sections and populated areas (Medeu et al. 2016).

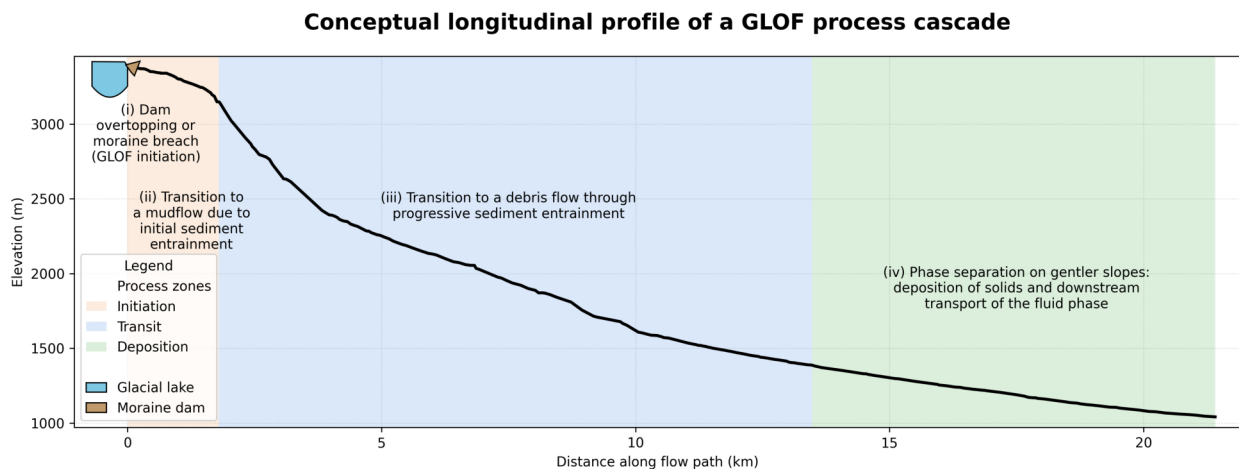


Figure 4.2.: Conceptual longitudinal profile illustrating the process cascade of a GLOF. The schematic shows the transition from dam over-topping or moraine breach (i), to an initial mudflow due to sediment entrainment (ii), followed by progressive sediment entrainment and transformation into a debris flow along the transport reach (iii), and finally phase separation with deposition of solids on gentler slopes while the fluid phase continues downstream (iv). The conceptual framework is adapted from Meyrat et al. (2024).

Taken together, these observations suggest that sediment entrainment along GLOF flow paths occurs in distinct, organised zones rather than being distributed uniformly or continuously. The relative dominance of erosion and deposition systematically shifts with channel gradient, valley confinement, and sediment availability, which exerts a primary control on the evolution of downstream flow. Figure 4.2 summarises these documented patterns by illustrating the characteristic

spatial organisation of sediment entrainment and the associated transformation of flow regimes along the flow path.

Documented patterns suggest that sediment entrainment during GLOF-related cascading mass flows is organised spatially along the flow path rather than being distributed uniformly. Distinct zones can be identified in which specific entrainment mechanisms dominate based on channel gradient, valley confinement, and sediment availability. To summarise these recurring patterns, Table 4.2 summarises the dominant entrainment mechanisms and their typical controlling conditions for the initial, transit, and depositional zones.

Table 4.2.: Flow path zonation of dominant sediment entrainment mechanisms during GLOF-related cascading mass flows. The table summarises documented entrainment processes in the initial, transit, and depositional zones, linking them to the typical controlling conditions reported in the literature. This zonation is based on observed patterns along GLOF flow paths and establishes a conceptual foundation for analysing dominant controls in Section 4.3.

Flow path zone	Dominant entrainment mechanism	Typical controlling factors	Key references
Initial zone	surface + local mass entrainment	Peak discharge, slope, channel confinement	Medeu et al. (2018); Rickenmann et al. (2024)
Transit zone	Surface + mass entrainment	Valley narrowing, sediment availability	Medeu (2011); Stepanov and Yafyazova (2014); Rickenmann (1999)
Deposition zone	Re-entrainment & deposition	Slope reduction, valley widening	Medeu et al. (2016); Rickenmann (1999); Rickenmann et al. (2024)

The zonation summarised in Table 4.2 highlights that sediment entrainment is governed by systematic interactions between hydrological forcing, channel geometry, and sediment availability along the flow path. These interactions not only control the spatial distribution of erosion and deposition, but also exert a primary influence on flow transformation and downstream hazard potential. The following section therefore examines the dominant controls on sediment entrainment in more detail.

4.2.3. Flow Transformation related to Sediment Entrainment

Sediment entrainment plays a central role in governing flow transformation during GLOF-related cascading processes. As illustrated in Figure 4.2, most documented events show a rapid transition from an initial outburst flood to a debris or mud-rock flow within a short downstream distance of the lake. This transformation is closely linked to progressive sediment uptake, which increases bulk density, viscosity, and internal friction. These changes alter flow rheology and dynamics (Medeu et al. 2016).

In the early phase, the released water behaves like a high-energy flood, capable of initiating bed and bank erosion. As sediment concentration increases, the flow progressively transforms into a debris-rich, highly viscous mass flow with plastic behaviour, enabling the transport of large boulders and the formation of block-rich, surge-like flow fronts. In extreme cases, interstitial water, derived from the lake, saturated sediments, melting ground ice, and entrained snow, significantly enhances flow mobility and runout distance (Medeu et al. 2016).

Several Ile-Alatau events demonstrate that this transformation process is self-reinforcing: increased sediment concentration enhances erosive power, which promotes further entrainment. Once a debris flow has fully developed, subsequent dilution by tributary inflows rarely reverses the transformation (Iverson, 1997). Instead, downstream evolution is dominated by progressive deposition and energy loss, which ultimately control runout length and impact zones (Medeu et al. 2016).

The reviewed case studies further indicate that flow transformation is sensitive to entrainment pathways. Events dominated by filtration-induced slope failures or moraine collapses tend to produce particularly dense, short-lived, yet highly destructive debris flows. In contrast, tunnel-drained outbursts more often result in mixed flood-debris-flow sequences. These distinctions underscore the importance of explicitly considering entrainment processes when conceptualising and modelling GLOF-related cascading mass flows (Popov et al. 2025).

Overall, the documented patterns of sediment entrainment in the Ile-Alatau case studies confirm several concepts described in the literature (Chapter 2), such as the importance of sediment availability and flow energy in amplifying debris flows. However, the observations also reveal stronger spatial persistence of downstream bulking and sediment uptake than is commonly assumed in generic GLOF frameworks. This emphasises the need for a more spatially explicit conceptualisation of entrainment processes. These documented spatial and process-based patterns provide the empirical basis for identifying the dominant controls on sediment entrainment, which are examined in the following section.

4.3. Dominant Controls on Sediment Entrainment

The relative importance of hydrological, geomorphometric, and sedimentological controls on sediment entrainment must be interpreted in the context of the regional characteristics of the Ile-Alatau catchments described in Chapter 3. Steep longitudinal gradients, short catchment response times, and widespread unconsolidated sediment storage strongly condition how these controls interact during GLOF-related mass flows.

As illustrated by the indicators summarised in Table 4.3, sediment entrainment during GLOF-related cascading mass flows is not controlled by a single factor, but rather by the interaction of hydrological forcing, geomorphometric conditions, and sediment availability along the flow path. High peak discharges, steep and confined channel sections, and the presence of weakly consolidated sediments are critical drivers of progressive entrainment and flow amplification.

The following subsections discuss these controls in more detail. Hydrological controls (subsection 4.3.1), geomorphometric controls (subsection 4.3.2), and sediment availability and source areas (subsection 4.3.3) are examined separately to clarify their individual roles and combined influence on sediment entrainment dynamics.

Table 4.3.: Key conceptual indicators controlling sediment entrainment and debris-flow amplification along GLOF-related flow paths in the Ile-Alatau Mountains. This table summarises the relevant hydrological, geomorphometric, and sedimentological processes that directly govern erosion, sediment uptake, and flow transformation. Only indicators directly relevant to sediment entrainment are included. The table serves as a conceptual synthesis and provides the basis for selecting empirical variables in Chapter 5.

Entrainment-relevant indicator	Role in sediment entrainment	Effect on flow evolution	Key References
High peak discharge / rapid lake drainage	Increases hydraulic shear stress on bed and banks	Initiation of channel incision and early sediment uptake	Medeu et al. (2022); Rickenmann et al. (2024)
Steep channel gradients ($\approx 10\text{-}25^\circ$)	Enhance flow velocity and erosive power	Efficient transformation from flood to debris flow	Medeu et al. (2022); Rickenmann et al. (2024)
Narrow and confined valley sections	Concentrate flow energy and shear stress	Localised deep incision and lateral erosion	Medeu (2011); Stepanov and Yafyazova (2014)
Abundant unconsolidated glacial and paraglacial sediments	Provide readily entrainable material along flow path	Strong amplification of flow volume and density	Medeu et al. (2016); Medeu et al. (2018)
Weakly consolidated moraine and valley-fill deposits	High erodibility under high-energy flows	Rapid entrainment and early debris-flow initiation	Yafyazova (2011); Stepanov and Yafyazova (2014)
Active bank erosion and slope failures	Supply sediment through mass entrainment processes	Pulsed increases in sediment concentration	Medeu et al. (2020); Zaginaev et al. (2019)
Progressive entrainment along the transit zone	Continuous interaction between flow and channel	Downstream increase in debris-flow magnitude	Rickenmann (1999); Rickenmann et al. (2024)
Downstream slope reduction and valley widening	Reduction in transport capacity	Deposition and phase separation in depositional zone	Rickenmann (1999); Meyrat et al. (2024)

4.3.1. Hydrological Controls

Hydrological forcing primarily controls sediment entrainment by determining flow energy, erosive capacity, and the potential for rapid flow transformation. Historical GLOF-related events in the Ile-Alatau region show that peak discharge alone cannot explain the magnitude of entrainment. Instead, the combination of discharge magnitude, flow duration, and hydrograph shape plays a decisive role (Medeu et al. 2016; Popov et al. 2025).

Events characterised by short-lived, high-magnitude water releases, such as the 1963 Issyk GLOF, produce extreme entrainment due to the combination of high shear stresses and sustained flow energy along steep, confined channels (Yafyazova, 2011). Conversely, events with lower peak discharges but prolonged flow duration, like the 1956 Tuyuksu event, achieved substantial downstream bulking through cumulative erosion and progressive sediment uptake (Medeu et al. 2016). These observations highlight that sustained hydrological forcing can compensate for moderate peak discharges, particularly in morphologically favourable settings (Medeu et al. 2016; Yafyazova, 2011).

Subglacial or intramoraine drainage pathways further modulate hydrological forcing by attenuating or redistributing the released water. Tunnel-dominated outbursts, as documented for the 1951 and 1958 events, initially limited erosion at the source, yet they did not prevent downstream amplification once surface flow and channelised erosion became dominant (Medeu et al. 2016; Yafyazova, 2011). Overall, hydrological controls govern the initial erosive impulse and strongly influence the efficiency of sediment entrainment during the early and intermediate stages of GLOF-related process cascades.

4.3.2. Geomorphometric Controls

Geomorphometric conditions determine where and how hydrological forcing translates into effective sediment entrainment. Channel gradient, valley confinement, and longitudinal profile discontinuities control flow acceleration, shear stress distribution, and the spatial concentration of erosion (Medeu et al. 2016).

Ile-Alatau case studies consistently demonstrate that the most intense entrainment occurs in steep, confined valley sections, especially where flows transition from morainic source areas to deeply incised trough valleys. For example, the Mynzhylky valley experienced rapid acceleration and strong lateral erosion during the 1956 and 1973 Tuyuksu events, which triggered extensive sediment mobilisation. Similarly, pronounced bulking zones were observed downstream of knick-points and valley constrictions in the Esik and Kaskelen basins (Medeu et al. 2016, 2020, 2022).

Conversely, wider valley sections with reduced gradients promote flow spreading, energy dissipation, and deposition, which limits further entrainment. The location of these geomorphometric thresholds explains why many high-magnitude debris flows retain destructive potential far downstream while smaller or supply-limited events attenuate rapidly (Medeu et al. 2020, 2022). These observations highlight the role of geomorphometry as a spatial filter governing the efficiency and persistence of sediment entrainment along the flow path.

4.3.3. Sediment Availability and Source Areas

Sediment availability is a key factor in entrainment efficiency, largely determining whether a GLOF-related event remains supply-limited or evolves into a highly destructive debris flow. The Ile-Alatau record shows that thick moraine deposits, relict erosion scars, and unstable valley fills greatly increase entrainment potential when there is enough hydrological forcing (Medeu et al. 2016; Popov et al. 2025).

Some events, such as the 1963 Issyk catastrophe and the 1973 Tuyuksu debris flow, illustrate how relatively small lake volumes can lead to large debris flows when large amounts of unconsolidated sediment are accessible along the flow path. Progressive erosion of moraines, remobilisation of older deposits, and slope failures contributed substantially more material than the initial lake release alone (Medeu et al. 2016; Yafyazova, 2011). In contrast, events such as the 1951 Kishi Almaty debris flow were largely supply-limited due to restricted sediment availability despite favourable hydrological conditions (Popov et al. 2025).

Repeated events within the same catchments further highlight the importance of sediment preconditioning. Reactivation of existing erosion cuts and previously destabilised moraines facilitated rapid entrainment during subsequent events, even under comparatively lower discharges, as documented in the Kaskelen and Talgar basins (Medeu et al. 2016; Popov et al. 2025; Yafyazova, 2011). These findings emphasise that sediment availability considers both present-day geomorphic conditions and the legacy of past events, which makes it a critical factor in controlling entrainment magnitude and downstream hazards.

In summary, hydrological forcing controls the initial erosive impulse, geomorphometric conditions determine the most efficient location for entrainment, and sediment availability establishes the upper limit of attainable debris-flow magnitude. This strong coupling explains why small glacial lakes can generate catastrophic debris flows while larger lakes may produce only limited impacts

under unfavourable conditions. This conceptual framework provides the basis for the quantitative parametrisation of sediment entrainment processes presented in Chapter 5.

4.4. Regional Characteristics of GLOF-Related Entrainment in Central Asia

Sediment entrainment related to GLOFs in Central Asia exhibits several regional characteristics that distinguish it from similar processes in other high-mountain regions. These characteristics stem from the region's unique combination of climatic conditions, glacial history, geomorphological features, and sediment availability (Medeu et al. 2016; Popov et al. 2025). Case studies from the Ile-Alatau Mountains illustrate how these regional factors systematically increase sediment entrainment and downstream flow amplification.

A defining regional feature is the pronounced relief energy combined with the short distances between glacial source areas and the valley floors downstream. Many catchments in the Ile-Alatau have elevation differences of several thousand metres over horizontal distances of less than 5-15 km, which promotes rapid flow acceleration and high shear stresses shortly after a lake outburst (Medeu et al. 2016). This topographic setting favors intense channel incision and lateral erosion, resulting in the early and efficient entrainment of sediment and the rapid transformation of water-dominated floods into debris-rich flows.

Another notable feature is the widespread presence of unconsolidated glacial and paraglacial sediments throughout the entire flow path. Thick moraine complexes, debris cones, talus slopes, and relict valley-fill deposits provide abundant material that can be mobilised once erosion thresholds are exceeded (Medeu et al. 2020; Yafyazova, 2011). Consequently, relatively small glacial lakes in the Ile-Alatau region have repeatedly generated debris flows whose final volumes have exceeded the initial water release by one or two orders of magnitude (Medeu et al. 2016).

Climatic conditions further reinforce these processes. In Central Asia, GLOFs often occur during periods of sustained high temperatures and/or intense rainfall. These conditions promote high meltwater input and elevated groundwater levels within moraine deposits (Popov et al. 2025). Saturated or thawing sediments have reduced shear strength, making them more susceptible to erosion and mass failure (Medeu et al. 2016). Consequently, sediment entrainment is strongly influenced by antecedent hydrometeorological conditions rather than by instantaneous discharge peaks alone.

Another regional characteristic is the strong legacy effect of past events. Many Central Asian catchments have experienced repeated GLOFs along the same flow paths. This has led to pre-conditioned channels with existing erosion scars, destabilised slopes, and partially remobilised sediment stores (Medeu et al. 2020, 2022). Subsequent events can therefore entrain sediment more efficiently, even under comparatively moderate hydrological forcing. This has been documented in the Kaskelen, Talgar, and Issyk basins (Yafyazova, 2011).

Taken together, these regional characteristics explain why GLOF-related sediment entrainment in Central Asia is often exceptionally efficient and extensive, capable of sustaining debris-flow behaviour far downstream. The combination of steep topography, abundant unconsolidated sediment, favourable climatic conditions, and geomorphic preconditioning causes downstream entrainment to dominate final hazard magnitude rather than lake volume alone (Medeu et al. 2016; Popov et al. 2025).

4.5. Conceptual Synthesis and Implications for Empirical Analysis

Building on the spatial patterns, controlling factors, and regional characteristics of sediment entrainment discussed above, this section presents a process-based conceptual framework integrating these insights to link GLOF initiation, downstream entrainment, and flow transformation.

4.5.1. Synthesis of Dominant Controls

A synthesis of documented GLOF events in the Ile-Alatau Mountains confirms that sediment entrainment is governed by a tightly coupled set of hydrological, geomorphometric, and sedimentological controls (Medeu et al. 2016; Popov et al. 2025). Hydrological forcing provides the initial energy necessary for erosion and sediment mobilisation. Geomorphometric conditions determine where this energy is most efficiently converted into entrainment. Sediment availability sets the upper limit of the volume of material that can be incorporated into the flow ultimately.

The reviewed case studies demonstrate that these controls do not act independently. Extensive entrainment does not necessarily result from high peak discharges when sediment availability is limited or when valley geometry promotes rapid energy dissipation, as observed during smaller events in the Kishi Almaty basin (Popov et al. 2025). Conversely, moderate hydrological forcing can lead to extreme debris flows when steep, confined channels intersect large stores of unconsolidated sediment, as demonstrated by the 1963 Issyk and 1973 Tuyuksu events (Medeu et al. 2016; Yafyazova, 2011).

Furthermore, entrainment efficiency evolves dynamically along the flow path. Initial conditions near the lake outlet influence early erosion. However, downstream channel morphology and sediment availability often exert greater control over the final magnitude of debris flows (Medeu et al. 2020). Thus, sediment entrainment emerges as a spatially distributed and path-dependent process rather than a phenomenon controlled solely by source characteristics.

4.5.2. Conceptual Model of Sediment Entrainment

Based on the synthesis of documented GLOF-related cascading mass-flow events, a conceptual model of sediment entrainment is proposed (Figure 4.3). The model describes how an initially water-dominated outburst flood interacts with steep, sediment-rich channels. This interaction initiates the erosion of the channel bed and banks once critical shear stresses are exceeded (Medeu et al. 2016). This initial erosion rapidly intensifies due to mass entrainment processes, including bank collapses, slope failures, and the remobilisation of pre-existing deposits (Yafyazova, 2011).

As illustrated in Figure 4.3, sediment entrainment intensity is the result of the combined interaction of hydrological forcing, geomorphometric controls, and sediment availability. Although the relative importance of these factors varies spatially along the flow path, their interaction governs entrainment intensity throughout the event. Progressive sediment uptake leads to a rheological transformation of the flow, shifting from a flood regime to a hyper-concentrated or debris-flow regime. This transformation enhances erosive power and promotes further entrainment, creating a positive feedback loop between sediment concentration and erosion efficiency (Medeu et al. 2016). Downstream flow evolution is ultimately constrained by geomorphometric thresholds, such as slope breaks and valley widenings, which regulate the transition from erosion-dominated to deposition-dominated behaviour (Medeu et al. 2020).

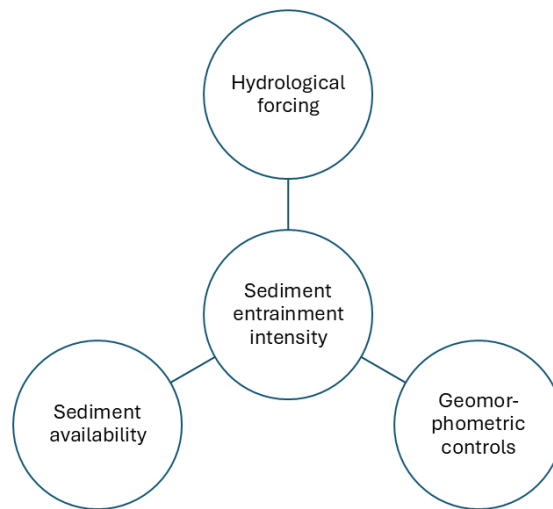


Figure 4.3.: Conceptual framework illustrating the interacting controls on sediment entrainment intensity during GLOF-related cascading mass flows. Hydrological forcing, geomorphometric controls, and sediment availability jointly influence sediment entrainment intensity along the flow path.

Although the conceptual model emphasises the interacting controls on entrainment intensity, documented case studies show that sediment entrainment is strongly structured along the flow path. As illustrated in Figure 4.2, entrainment is typically most pronounced in the upper to middle sections of the catchment. However, downstream sections are increasingly characterised by deposition as flow energy declines or sediment supply becomes limited. This spatial pattern is consistent with observations from the Ile-Alatau basins (Medeu et al. 2022).

4.5.3. Identified Research Gaps

The conceptual synthesis highlights that quantitative constraints on entrainment remain limited for Central Asian GLOF-related process chains. In particular, systematic measurements of erosion depths, entrained sediment volumes, and spatial variations in entrainment rates along complete flow paths are scarce, as most historical events lack post-event surveys suitable for process quantification (Medeu et al. 2016; Popov et al. 2025). As a result, model validation and the derivation of transferable entrainment relationships remain challenging.

A second gap concerns the attribution of entrainment to individual controls under different boundary conditions. While the reviewed case studies consistently point to the interplay of hydrological forcing, geomorphometry, and sediment availability, few studies quantify their relative importance at the catchment scale or along the flow path (Medeu et al. 2020). In particular, sediment availability and geomorphic preconditioning are frequently acknowledged but rarely represented explicitly through reproducible metrics, which limits comparability across events and regions.

4.5.4. Implications for Empirical Analysis

The conceptual framework developed in this chapter lays the groundwork for the empirical analyses presented in Chapter 5. The dominant controls on sediment entrainment, which are identified here, guide the selection of parameters used to quantify entrainment processes at the catchment scale. Hydrological forcing is represented by parameters that describe lake volume and peak outburst discharge. Geomorphometric controls are captured using terrain metrics, such as channel slope characteristics and valley form. Sediment availability is approximated using indicators of

sediment storage and the presence of remobilisable deposits along the flow path. The translation of these conceptual controls into measurable parameters is summarised in Table 4.4.

Hydrological forcing is the initial driver of sediment entrainment, determining the magnitude and energy of the outburst flood. Previous studies have demonstrated that peak discharge and released water volume have a strong influence on a flow's ability to exceed critical shear stress thresholds and initiate the erosion of channel beds and banks (Iverson, 2012; Worni et al. 2013). Although hydrological parameters alone cannot explain the downstream evolution of GLOFs, they are essential for assessing the potential intensity of entrainment processes. Therefore, empirical parameters describing lake volume and peak outburst discharge are required to represent the system's initial forcing.

Beyond hydrological triggering, the efficiency of sediment entrainment is strongly influenced by the geomorphometric characteristics of the flow path. Channel slope, valley confinement and longitudinal variability in terrain geometry influence the acceleration of flow, the concentration of energy and the efficiency of erosion in debris-flow-like mass movements (Hungri et al. 2005; Rickenmann, 1999). Steep, confined channel sections promote intense incision and lateral erosion, whereas lower-gradient or wider sections favour deposition and temporary sediment storage (Mergili, 2016). These findings suggest that geomorphometric controls should be evaluated along the entire flow path rather than at specific locations. Accordingly, terrain metrics based on the flow path are required to capture the spatial variability of entrainment conditions at the catchment scale.

The availability of sediment is another critical prerequisite for substantial entrainment. Numerous studies have shown that, in high-mountain environments, particularly in glaciated and paraglacial catchments, the magnitude of debris-rich flows is often limited not by water volume, but by the presence and connectivity of unconsolidated sediment sources (Hungri et al. 2005; Westoby et al. 2014a). In regions such as the northern Tien Shan, moraines, talus slopes, channel fills and older debris-flow deposits provide extensive stores of weakly consolidated material that can be rapidly mobilised during GLOFs (Zaginaev et al. 2016). As direct quantitative data on sediment volumes is rarely available, sediment availability is typically estimated using geomorphological indicators that reflect the presence of remobilisable deposits along the flow path.

Table 4.4.: Translation of conceptual controls on sediment entrainment into the empirical parameters used. The table links the dominant hydrological, geomorphometric, and sediment-related controls identified in Chapter 4 to the measurable parameters applied in the catchment-scale analysis. Only parameters representing explanatory controls are included. Process and impact characteristics are introduced separately in Chapter 5.

Conceptual control	Empirical parameter (this study)	How it was derived / classified	What it represents for entrainment
Hydrological forcing	Lake volume [m ³]	Taken from published databases / literature per event	Initial water supply and potential magnitude of the outburst trigger
	Peak outburst discharge [m ³ /s]	Taken from published databases / literature per event	Event intensity / flow energy available to initiate erosion and sediment uptake
Geomorphometric controls	Mean slope gradient [°]	Derived along reconstructed flow path from DEM	Overall steepness controlling shear stress potential and erosion efficiency
	Median slope gradient [°]	Derived along reconstructed flow path from DEM	Robust measure of typical channel steepness (less sensitive to extremes)
	Maximum slope gradient [°]	Derived along reconstructed flow path from DEM	Local extreme steep sections that may act as entrainment “hotspots”
	Share of slope classes [%] : <10 °, 10–25 °, >25 °	Flow path segmented by slope; class thresholds after Medeu et al. (2022)	Spatial distribution of low/medium/high-energy reaches controlling where entrainment vs deposition dominates
	Valley form classification [%] : U-shaped, V-shaped, intermediate	Cross-sections extracted along flow path; classified by profile geometry	Confinement / channel morphology influencing erosion type (incision vs. lateral erosion) and flow focusing
Sediment availability	Moraine sediment share [%]	Visual interpretation along flow path (remote sensing imagery)	Availability of weak, easily erodible glacial sediments for rapid bulking
	Landslide sediment share [%]	Visual interpretation along flow path	Potential for episodic mass entrainment (bank collapse / slope failures)
	Channel-derived sediment share [%]	Visual interpretation along flow path	Readily entrainable sediment stored in the channel / valley bottom
	Floodplain sediment share [%]	Visual interpretation along flow path	Depositional storage and potential re-entrainment in lower-gradient reaches

By translating conceptual controls into measurable parameters, their relative importance and interaction effects can be systematically evaluated across multiple catchments in Chapter 5. This enables a quantitative assessment of how regional hydrological and geomorphological variability influences sediment entrainment during GLOFs in the Ile-Alatau Mountains and provides a transparent basis for the empirical analysis. These gaps motivate a catchment-scale, flow path-based empirical analysis that integrates hydrological forcing with geomorphometric and sediment-source indicators.

5. Empirical Analysis of Controls on Sediment Entrainment

This chapter presents the empirical analysis of the controls on sediment entrainment in GLOF-related cascading mass flows in the Ile-Alatau Mountains. It combines the methodological workflow with the resulting empirical findings. This analysis is based directly on the conceptual framework developed in Chapter 4, specifically the selection of GLOF events (Table 4.1) and the definition of hydrological, geomorphometric, and sedimentological parameters (Table 4.4).

5.1. Data Compilation and Pre-Processing

This section describes how the datasets used for the empirical analysis were compiled and pre-processed. It outlines how topographic and optical imagery data were acquired and the subsequent processing steps required to derive hydrologically consistent flow paths and geomorphometric information.

5.1.1. Baseline Topographic and Imagery Data

The objective of this step was to compile and prepare the necessary topographic and visual baseline datasets for the empirical analysis. The primary topographic dataset was a digital elevation model (DEM) with a spatial resolution of 30 meters, which was provided by the Copernicus program (Copernicus Sentinel data, 2025). Acquired on April 18, 2011, the DEM served as the basis for all geomorphometric analyses and flow-path reconstructions. Although the DEM predates some events, its use is justified because large-scale valley geometry and channel gradients remain stable over decadal timescales. DEM-based terrain analysis and flow-path derivation are widely applied approaches in geomorphological and hazard-related studies and provide a consistent basis for catchment-scale analyses (Mergili et al. 2017; Tarboton, 1997). Both the DEM and Sentinel data were downloaded via the Copernicus Data Space Browser (Copernicus Sentinel data, 2025).

Optical satellite imagery was used for geomorphological interpretation and sediment source identification. Where possible, cloud-free Sentinel-2 imagery acquired on June 28, 2025, with a spatial resolution of 10 meters was selected to ensure optimal surface visibility. Additionally, high-resolution Google satellite imagery from 2025 served as the primary visual reference for detailed geomorphological interpretation. The use of multi-source optical imagery for identifying erosion features, channel morphology, and sediment storage areas is a common approach in geomorphological studies, particularly in data-scarce high-mountain environments (Bolch et al. 2011; Mergili, Schneider, et al. 2011).

This imagery was used to identify channel incisions, erosion zones, and sediment storage areas along the reconstructed flow paths. When areas of interest were obscured by clouds or snow in the 2025 Google imagery, images from previous years were consulted to ensure a reliable interpretation. Sentinel-2 imagery served primarily as a supplementary dataset and was used when geomorphological features were not clearly identifiable in the available Google imagery.

5.1.2. Hydrological Correction and Flow Network Derivation

The baseline datasets were processed hydrologically and geometrically to establish a consistent foundation for the analysis. All processing steps were carried out in QGIS version 3.40.6.

To ensure a physically consistent drainage structure, the Copernicus DEM was first hydrologically corrected. Internal sinks were removed using a sink-filling algorithm to eliminate spurious depressions and enforce continuous downstream flow. Hydrological correction of DEMs is a standard pre-processing step in flow-routing and catchment-scale geomorphological analyses, particularly when DEMs are used to derive flow direction and accumulation patterns (Jenson & Domingue, 1988; Tarboton, 1997).

Following hydrological correction, flow direction and flow accumulation were calculated, and the river network was extracted based on a flow accumulation threshold of 200 raster cells (equivalent to approximately 0.18 km² contributing area at 30 m resolution). The resulting drainage network was converted to vector format to obtain continuous flow paths. Hillshade visualisations were used to assess the consistency of the derived drainage structure and to identify potential artefacts related to terrain representation. DEM-based flow network extraction combined with visual validation is a commonly applied approach in geomorphological and hazard-related studies to ensure plausible flow-path geometry (Mergili et al. 2017; Tarboton, 1997).

Finally, the derived flow paths were visually checked against high-resolution optical imagery and manually adjusted where necessary to account for DEM-related artefacts and to better represent observed channel alignments. Manual refinement based on remote sensing imagery is commonly applied in high-mountain terrain, where DEM resolution and surface conditions can limit the accuracy of fully automated flow-routing approaches (Westoby et al. 2014a).

5.2. Derivation of Process-Relevant Controlling Factors

The analysis of sediment entrainment controls was conducted based on the conceptual framework presented in Chapter 4. The empirical analysis therefore explicitly tests the conceptual assumptions regarding the relative importance and interaction of hydrological, geomorphometric, and sedimentological controls. The parameters used in the empirical analysis correspond to those in Table 4.4, and the analysed GLOF events are listed in Table 4.1.

5.2.1. Hydrological Forcing Parameters

Hydrological forcing is the initial driver of GLOF-related cascading mass flows, providing the boundary conditions for downstream sediment entrainment. This subsection describes the hydrological parameters used to characterise the magnitude of the analysed GLOF events.

Method

Hydrological parameters were derived exclusively from published literature and established GLOF databases, as described in Section 4.1. These parameters include the initial outburst water volume and the reported peak discharge of the analysed GLOF events. Peak discharge and released water volume are commonly used first-order descriptors of GLOF magnitude and erosive potential, particularly in comparative or regional-scale analyses where detailed hydrographs are unavailable (Walder & Costa, 1996; Westoby et al. 2014a). Additional hydrological modelling was not performed, as the required parameters were documented for all selected events and reported

consistently across sources. This approach ensures methodological consistency across events and aligns with the conceptual framework presented in Chapter 4.

To quantitatively characterise the relationship between lake volume and peak discharge within the Ile-Alatau dataset, an empirical scaling relation was derived following the general approach proposed by Huggel et al. (2002), who evaluated volume–discharge relations for glacier lake outbursts in the Swiss Alps. In accordance with widely applied empirical GLOF scaling approaches, a power-law relationship of the general form

$$Q = \alpha V^\beta \quad (5.1)$$

was assumed. To estimate the scaling parameters for the regional dataset, a linear regression was performed in logarithmic space using ordinary least squares (OLS). The regression model is expressed as:

$$\log_{10}(Q) = \log_{10}(\alpha) + \beta \log_{10}(V) \quad (5.2)$$

where β represents the scaling exponent and α the multiplicative coefficient after back- transformation to linear space.

The regression parameters were estimated using unweighted ordinary least squares in logarithmic space. Reported uncertainties in peak discharge were not propagated, as uncertainty ranges were inconsistently documented across sources and not comparable between events. The derived relation therefore represents an empirical regional scaling intended for comparative evaluation rather than a process-based predictive model. The coefficient of determination (R^2) was used to assess the goodness of fit.

In contrast to Huggel et al. (2002), who derived empirical relations from a combined Alpine dataset, the present study establishes a region-specific scaling relation based exclusively on documented GLOF events in the Ile-Alatau. This allows assessment of potential regional deviations from globally reported scaling behaviour.

To further contextualise the derived regional relation, selected published empirical volume– discharge relationships were compiled from the literature (see Appendix B). These include scaling relations developed for glacier-dammed and moraine-dammed lakes in different mountain regions (e.g., Clague and Mathews, 1973; Evans, 1986; Haeberli, 1983; Huggel et al. 2002; Popov, 1991; Walder and Costa, 1996). The published relations were plotted over the observed range of lake volumes without recalibration to enable direct comparison with the Ile-Alatau events.

The regression and comparative analysis were restricted to the observed data domain and no extrapolation beyond the range of documented lake volumes was performed.

Results

The hydrological characteristics of the analysed events are summarised in Table 5.1. The initial outburst water volumes vary by more than an order of magnitude from event to event. Peak outburst discharge also shows pronounced variability across events, ranging from a few cubic metres per second to several hundred cubic metres per second. This variability provides a suitable basis for evaluating the role of hydrological forcing in sediment entrainment and flow amplification.

Table 5.1.: Hydrological characteristics of the analysed GLOF events in the Ile-Alatau. The table lists the catchment, glacier and lake involved, event date, estimated lake volume prior to outburst, and peak outburst discharge for each event. Lake volume and peak discharge values are compiled from published reconstructions (see Appendix A.1 for detailed event-specific references).

Catchment	Glacier	Lake	Date of Outburst	Volume of lake [m ³]	Discharge of outburst [m ³ /s]
Kaskelen	No. 25	No. 16	23.07.1980	286,000	23
Kaskelen	No. 25	No. 16	05.07.1986	140,000	60
Kargaly	Kargalinka	No. 1	23.07.2015	80,000	5
Kargaly	Kargalinka	No. 1	14.08.2019	200,000	5
Ulken Almaty	Kumbel	No. 14	19.08.1975	5,000	4
Ulken Almaty	Sovetov	No. 13	03.08.1977	82,000	210
Kishi Almaty	Central Tuyksu	No. 2	20.08.1951	20,000	50
Kishi Almaty	Central Tuyksu	No. 2	07.08.1956	32,000	32
Kishi Almaty	Central Tuyksu	No. 2, No. 3	15.07.1973	224,000	350
Talgar	Spotivnyi	No. 7	21.06.1979	82,000	15
Talgar	Bezmyannyi	No. 8	06.07.1993	100,000	15
Talgar	Bezmyannyi	No. 8	17.07.2014	50,000	5
Issyk	Zharsay	No. 17	06.07.1958	250,000	221
Issyk	Zharsay	No. 17	07.07.1963	460,000	800
Issyk	Zharsay	No. 17	03.07.1977	430,000	40

Figure 5.1 shows the relationship between pre-outburst lake volume (V) and reported peak discharge (Q) for the analysed Ile-Alatau events (blue dots) in log space. The dashed lines represent published empirical scaling relations derived from global or Alpine datasets (see Appendix B). The solid line indicates a region-specific power-law regression fitted to the Ile-Alatau dataset. The resulting relationship follows

$$Q = 0.01 V^{0.69} \quad (5.3)$$

with a coefficient of determination of $R^2 = 0.25$, indicating substantial scatter and limited explanatory power of lake volume alone, despite a positive scaling tendency.

The comparison illustrates that the Ile-Alatau events scatter widely around the published relations. The derived regional scaling relation ($R^2 = 0.25$) indicates that lake volume alone explains only a limited proportion of discharge variability. This suggests that additional regional factors, such as dam type, breach mechanics, and channel geometry, exert significant control on peak outburst discharge.

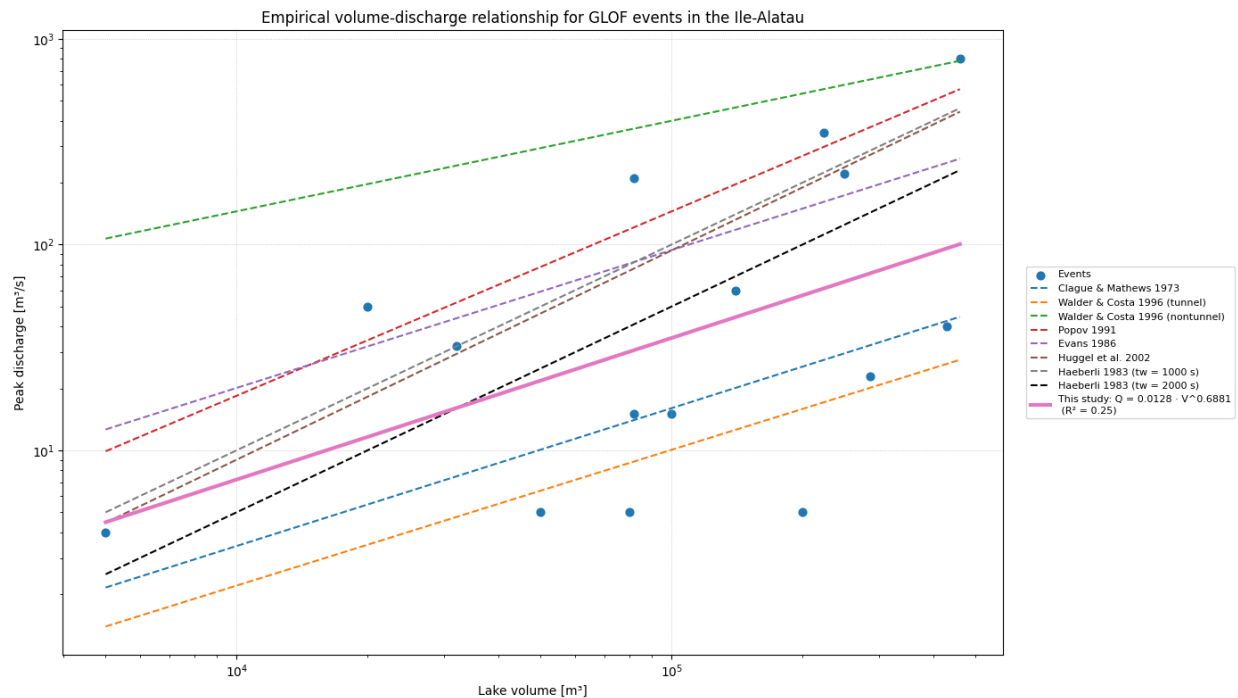


Figure 5.1.: Relationship between pre-outburst lake volume (V) and reported peak outburst discharge (Q) for analysed GLOF events in the Ile-Alatau (log scale). Published empirical scaling relations (dashed lines; see Appendix B) and a region-specific power-law fit (solid line) are shown for comparison. Conceptual structure adapted from Huggel et al. (2002).

5.2.2. Geomorphometric Controls along the Flow Path

The geomorphometric characteristics along the flow path determine the potential for sediment mobilisation and flow transformation during downstream propagation. This subsection focuses on how slope gradients and valley geometry are key geomorphometric controls on sediment entrainment.

Method

The geomorphometric analysis was based on a hydrologically corrected DEM and reconstructed flow paths. All geomorphometric metrics were derived using a reproducible GIS–Python workflow. Prior to analysis, the DEM and flow paths were handled in a GIS environment for verification of geometric consistency and attribute integrity. Subsequent extraction and classification steps were automated in Python (version 3.9.21) to ensure consistent processing across all catchments. The Python script for longitudinal profile processing and slope classification is provided in Appendix C, while the automated cross-section and valley classification workflow is documented in Appendix C.

Longitudinal profiles were extracted from each reconstructed flow path in order to quantify slope gradients and longitudinal variability. For this purpose, the flow paths were exported as 3D polylines (x, y, z) and processed using a Python routine that removed spurious uphill steps in the elevation sequence, simplified near-linear vertices to stabilise local gradient estimates, and computed cumulative channel distance and continuous local slope between consecutive vertices. Channel slope was calculated continuously along the flow paths and classified into three slope categories: $<10^\circ$, $10\text{--}25^\circ$, and $>25^\circ$. These categories reflect empirically established process regimes that differ in terms of erosion efficiency and sediment entrainment potential in GLOF- and mudflow-related

processes. Low-gradient sections ($<10^\circ$) generally have limited entrainment capacity, whereas moderate to steep slopes promote increased sediment mobilisation and flow transformation. Very steep sections ($>25^\circ$) are particularly relevant for intense entrainment due to the combined effects of high flow energy and hillslope instability. The adopted slope thresholds were taken from Medeu et al. (2022) to ensure consistency with regional studies and enable a comparable classification across all investigated catchments.

To characterise valley geometry, cross-sections were automatically generated along each flow path by constructing orthogonal transects at 200 m intervals. Each cross-section was 500 m wide, extending 250 m to either side of the reconstructed channel centreline. DEM elevations were sampled at regular intervals along each transect to derive cross-sectional metrics. The local valley relief for each cross-section was defined as the difference in elevation between the maximum and minimum elevations within the profile. Following established morphometric concepts of valley geometry, the valley floor was identified as the lower portion of the cross-section whose elevation did not exceed 20% of the local relief above the minimum elevation (Harbor, 1992). The ratio of valley floor width to total cross-sectional width (floor width ratio) was used as an indicator of valley form (Anderson et al. 2006; Harbor, 1992). Cross-sections with floor width ratios of ≥ 0.30 were classified as U-shaped valleys, those with ratios of ≤ 0.15 as V-shaped valleys and those with intermediate values as transitional forms. These thresholds represent idealised end-member valley morphologies and were applied consistently across all flow paths and catchments.

Results

The geomorphometric characteristics of the analysed GLOF flow paths are summarised in Table 5.2, while detailed longitudinal profiles and spatial slope distributions are provided in Appendix D. The elevation differences (ΔH) between lake outlets and distal impact areas range from approximately 740 m a.s.l. to more than 2,500 m a.s.l., reflecting the pronounced relief across all investigated catchments. Lake elevations generally exceed 3,300 m a.s.l., whereas impact elevations are typically located between about 950 m a.s.l. and 2,500 m a.s.l.

Mean slope gradients along the flow paths vary between approximately 4.7° and 16.5° , with median values ranging from about 3.1° to 17.1° . Despite these predominantly moderate mean gradients, maximum local slopes exceed 30° in most catchments, reaching nearly 37° , indicating the presence of spatially confined but potentially process-relevant steep sections.

The relative distribution of slope-gradient classes is illustrated in Figure 5.2a. Low slope gradients ($<10^\circ$) clearly dominate most events, typically accounting for 70–90% of the total flow path length. Intermediate gradients ($10\text{--}25^\circ$) contribute variably between catchments (approximately 10–33%), whereas steep sections ($>25^\circ$) generally represent only a minor fraction, usually less than 3%. An exception is the Talgar 1979 event, which exhibits a comparatively higher proportion of intermediate to steep slopes, consistent with its elevated mean and median gradients (see Table 5.2). Longitudinal profiles further indicate that steeper segments are mainly concentrated in upstream sections, while gentler slopes prevail downstream (Appendix D).

Valley morphology exhibits similarly systematic patterns (Figure 5.2b). U-shaped valleys dominate most flow paths, accounting for approximately 40–75% of their total length. V-shaped sections are generally limited ($<15\%$), whereas intermediate valley forms contribute between 15% and 45%, depending on the catchment. The longitudinal profiles (Appendix D) reveal a consistent spatial trend: confined V-shaped sections occur primarily in upstream reaches, while wider U-shaped and transitional forms increasingly characterise downstream segments.

Table 5.2.: Geomorphometric characteristics of the analysed GLOF flow paths in the Ile-Alatau. The table summarises elevation differences (ΔH), lake and impact elevations, mean, median, and maximum slope gradients, the relative distribution of slope classes along the flow paths, and the proportions of different valley types (U-shaped, V-shaped, and intermediate).

Catchment	Glacier	Lake	Dates of outburst	ΔH [m]	Height Lake [m]	Height Impact [m]	$\emptyset$ slope gradient [°]	Median slope gradient [°]	Max Slope gradient [°]	Share <10° [%]	Share 10-25° [%]	Share >25° [%]	Share U- valley [%]	Share V-valley [%]	Share valley intermediate [%]
Kaskelen	No. 25	No. 16	23.07.1980	2346	3425	1079	4.7	3.5	23.2	90.7	9.3	0	76.8	8.7	14.5
Kaskelen	No. 25	No. 16	05.07.1986	2346	3425	1079	4.7	3.5	23.2	90.7	9.3	0	76.8	8.7	14.5
Kargaly	Karga-linka	No. 1	23.07.2015	2526	3523	997	6.3	5.4	31.5	87.8	12.1	0.1	49.6	12.4	38.1
Kargaly	Karga-linka	No. 1	14.08.2019	2180	3523	1343	7.1	6.2	31.5	84.1	15.7	0.2	41.9	14	44.2
Ulken Almaty	Kumbel	No. 14	19.08.1975	2167	3460	1293	7.3	4.9	34.3	72.7	25.9	1.4	69	3.6	27.4
Ulken Almaty	Sovetov	No. 13	03.08.1977	1957	3380	1423	7.6	5.4	30	76.3	21.1	2.5	59.5	6.8	33.8
Kishi Almaty	Central Tuyksu	No. 2	20.08.1951	2244	3382	1138	6.5	4.9	29.4	81.3	18.2	0.6	67	4.1	28.9
Kishi Almaty	Central Tuyksu	No. 2	07.08.1956	2437	3382	945	5.7	4.5	29.4	84.7	14.8	0.5	67.2	4.2	28.6
Kishi Almaty	Central Tuyksu	No. 2, No. 3	15.07.1973	1541	3374	1833	8.9	8.7	21.8	66.8	33.2	0	46	6	48
Talgar	Spotivnyi	No. 7	21.06.1979	742	3230	2488	16.5	17.1	34.7	24.2	61.2	14.6	69.2	23.1	7.7
Talgar	Bezymy-annyi	No. 8	06.07.1993	2343	3385	1042	6.1	4.1	36.9	83.5	14.6	1.9	67.9	7.5	24.5
Talgar	Bezymy-annyi	No. 8	17.07.2014	2224	3385	1161	6.9	4.5	36.9	80.5	17.3	2.3	68.5	6.7	24.7
Issyk	Zharsay	No. 17	06.07.1958	1662	3380	1718	6.4	3.3	29.1	76.4	22.7	0.9	75	2.8	22.2
Issyk	Zharsay	No. 17	07.07.1963	2167	3380	1213	5.5	3.1	29.1	82.5	16.9	0.6	77.1	4.6	18.3
Issyk	Zharsay	No. 17	03.07.1977	1572	3380	1808	7.4	4.2	29.1	71.1	27.8	1.1	72.4	5.2	22.4

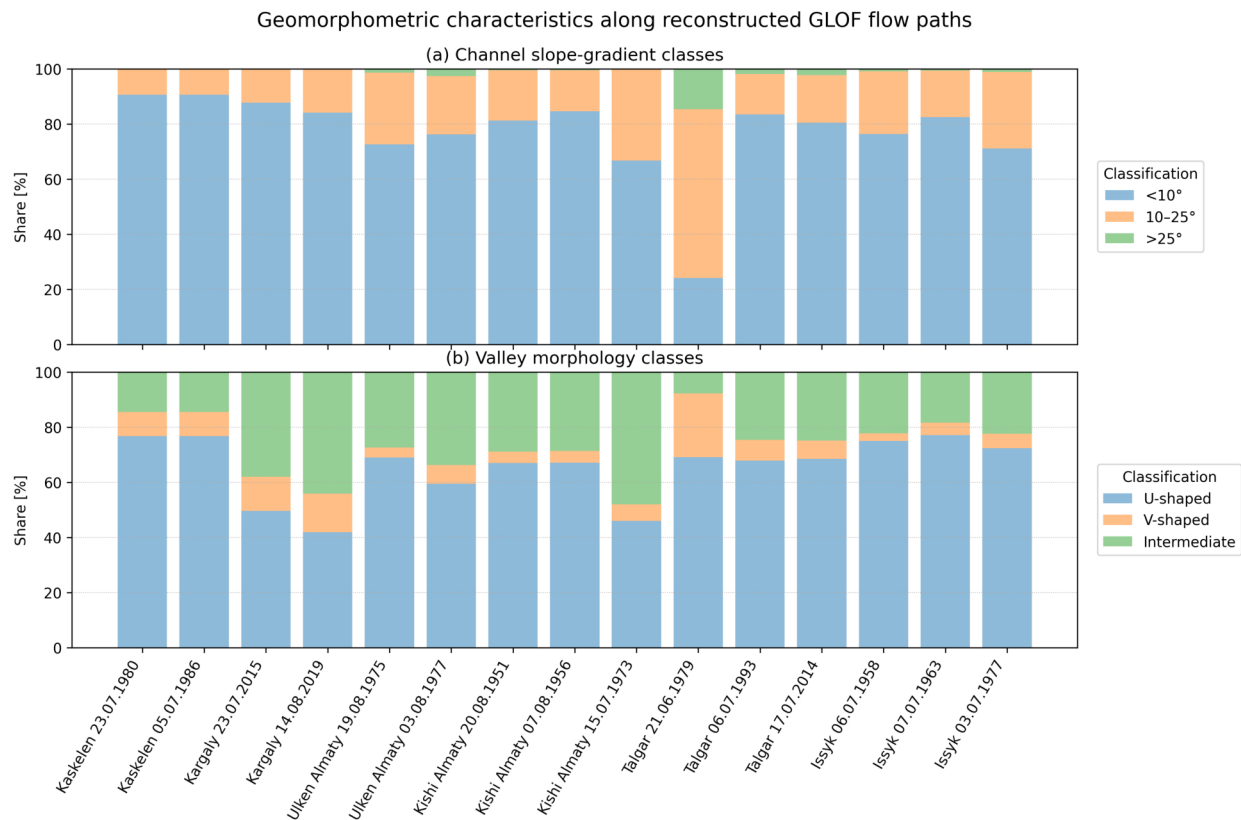


Figure 5.2.: Geomorphometric characteristics along reconstructed GLOF flow paths in the Ile-Alatau. (a) Relative distribution of channel slope-gradient classes (<10°, 10–25°, >25°). (b) Relative distribution of valley morphology classes (U-shaped, V-shaped and intermediate) along each flow path. Bars are normalised to 100% for each event, representing the proportional share of each class along the total reconstructed flow path length.

5.2.3. Sedimentological Controls and Sediment Availability

Sediment availability along the flow path is a fundamental prerequisite for volume amplification in GLOF-related mass flows. This subsection evaluates the spatial distribution and relative contribution of potential sediment sources that are intersected by the reconstructed flow paths.

Method

The sediment source areas were delineated using a combined document- and image-based interpretation approach. First, the GLOF event reports and process descriptions documented in Appendix A were analysed systematically to identify the sediment sources, erosion zones and documented flow transformations that were explicitly mentioned. These text-based reconstructions provided an initial framework for identifying the dominant types of sediment source along each reconstructed flow path.

The identified sediment sources were then spatially interpreted and manually digitised in a GIS environment over high-resolution Google satellite imagery. The reconstructed flow paths were overlaid on the imagery to verify the geomorphic plausibility of the documented sediment sources

and to map their spatial extent. Mapping was based on consistent visual criteria, including surface colour contrasts, texture, geomorphological setting, and spatial connectivity to the channel. Moraine complexes were identified by ridge-like or arcuate landforms, slope failures by visible scarps and debris lobes, and channel-bound accumulations by bar-like or braided channel patterns. These represent the dominant sediment sources in glaciated and paraglacial high-mountain environments (Hungre et al. 2005; Westoby et al. 2014b).

The spatial intersection and proportion calculations were performed using Python-based geospatial analysis tools to ensure reproducibility and consistency across all case studies (see Appendix C). The relative contribution of each sediment source type was quantified by intersecting the mapped sediment polygons with the reconstructed flow paths and calculating the proportion of each flow path that passed through or was directly adjacent to each sediment category. The resulting percentages therefore represent spatial sediment connectivity along the runout path rather than volumetric sediment supply. Sediment availability is interpreted as spatially connected sediment exposure rather than total sediment volume, which is consistent with comparative regional-scale approaches where quantitative sediment data are unavailable (Hungre et al. 2005; Zaginaev et al. 2019).

Uncertainty arises from potential ambiguities in the event documentation and constraints on image resolution, as well as from the effects of illumination and shadows, and the subjective delineation of sediment boundaries. As the sediment source areas were identified through document-guided visual interpretation without field validation, the mapped boundaries should be considered approximate. This primarily affects the exact spatial extent of the sediment sources, and therefore the calculated proportional values. Consequently, the results should be interpreted as semi-quantitative indicators of relative sediment availability rather than as precise quantitative measurements.

Results

Table 5.3 summarises the spatial distribution of sediment sources and process zones along the reconstructed GLOF flow paths, while the relative event-scale composition is visualised in Figure 5.3. Most flow paths intersect multiple sediment-rich zones, highlighting the pronounced spatial heterogeneity in sediment availability along the transport corridors. The stacked bar representation illustrates clear contrasts in source dominance between catchments.

In most analysed catchments, channel-stored sediments constitute the dominant sediment source, commonly accounting for more than 40–80% of the mapped sediment zones (Figure 5.3). Moraine material represents a secondary but locally important contribution, particularly in the Talgar 1979 event, where morainic sediments comprise a comparatively large share relative to other events.

Landslide-derived sediments show strong inter-event variability. They contribute substantially in the Ulken Almaty and Kishi Almaty events, where landslide-related material represents more than 30–40% of the mapped sediment sources. In contrast, landslide contributions are negligible in several Kaskelen and Kargaly events. Floodplain sediments generally play a subordinate role in upstream-dominated systems but become more relevant in selected Talgar and Issyk events, where they locally account for up to approximately 40% of the mapped sediment zones.

Overall, the results demonstrate pronounced spatial contrasts in sediment-source composition between catchments. The proportional differences shown in Figure 5.3 underline the substantial heterogeneity in sediment availability along GLOF flow paths in the Ile-Alatau region, which

likely exerts a first-order control on downstream sediment entrainment and flow transformation processes (see Appendix D for spatial configuration).

Table 5.3.: Relative contribution of different sediment source types along the GLOF flow paths for the analysed events in the Ile-Alatau. Shown are the percentages of morainic, channel-derived, landslide-related, and floodplain sediments identified along each flow path.

Catchment	Glacier	Lake	Dates of outburst	Share Moraine [%]	Share Channel [%]	Share Landslide [%]	Share Floodplain [%]
Kaskelen	No25	No. 16	23.07.1980	4.5	86.7	4.6	4.3
Kaskelen	No25	No. 16	05.07.1986	4.5	86.7	4.6	4.3
Kargaly	Kargalinka	No. 1	23.07.2015	8.7	89.1	0	2.3
Kargaly	Kargalinka	No. 1	14.08.2019	8.7	89.1	0	2.3
Ulken Almaty	Kumbel	No. 14	19.08.1975	2.5	55.5	36.5	5.6
Ulken Almaty	Sovetov	No. 13	03.08.1977	8.3	56.5	27	8.2
Kishi Almaty	Central Tuyksu	No. 2	20.08.1951	13.9	33.8	42.6	9.7
Kishi Almaty	Central Tuyksu	No. 2	07.08.1956	14.6	35.4	42.2	7.8
Kishi Almaty	Central Tuyksu	No. 2, No. 3	15.07.1973	14.2	34.6	41.2	9.9
Talgar	Spotivnyi	No. 7	21.06.1979	43.8	46.3	0	9.9
Talgar	Bezmyannyi	No. 8	06.07.1993	8.4	42.4	10.2	38.9
Talgar	Bezmyannyi	No. 8	17.07.2014	8.8	40.1	10.6	40.5
Issyk	Zharsay	No. 17	06.07.1958	14.8	38	20.6	26.7
Issyk	Zharsay	No. 17	07.07.1963	9.9	32.1	19.8	38.3
Issyk	Zharsay	No. 17	03.07.1977	21.2	18.3	29.5	31

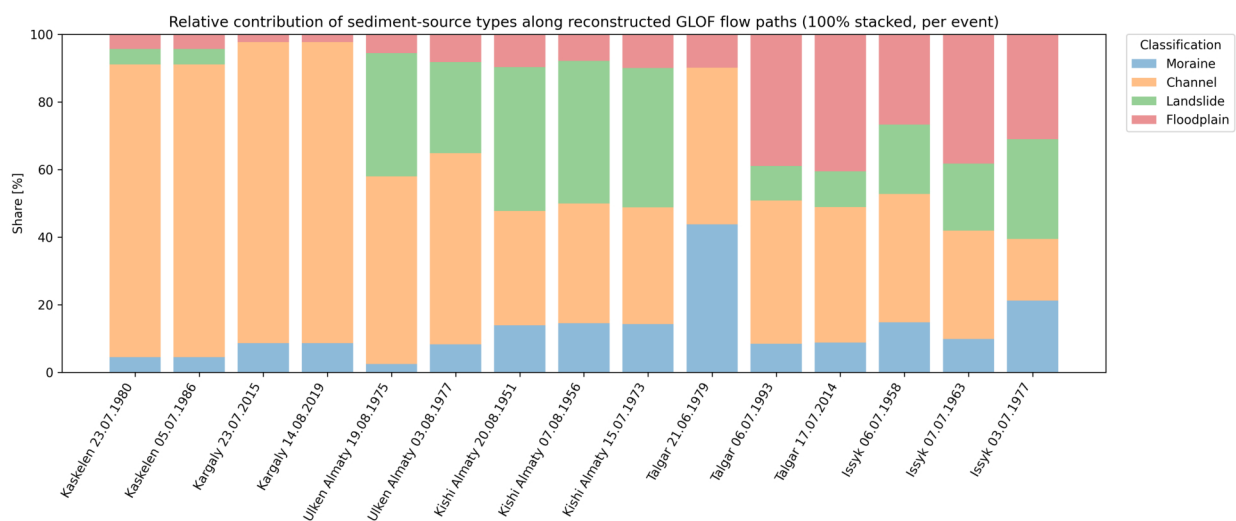


Figure 5.3.: Relative contribution of mapped sediment-source types along reconstructed GLOF flow paths in the Ile-Alatau. Bars indicate event-scale proportions of morainic, channel-derived, landslide-related, and floodplain sediments, expressed as 100% stacked percentages for each documented event.

5.3. Statistical Modelling of Controls on Sediment Entrainment

To investigate the controls on sediment entrainment and discharge amplification, this section evaluates the combined influence of hydrological, geomorphometric and sedimentological factors across the analysed GLOF events. Dimensionless response metrics were introduced to allow comparison between events of differing magnitude. Exploratory correlation analysis and regression-based model comparison were then applied, including interaction terms to test for non-additive process coupling.

5.3.1. Exploratory Analysis

An exploratory analysis was conducted to identify the dominant relationships between the controlling factors and the sediment-related response metrics. This step establishes the foundation for subsequent regression modelling by identifying consistent and physically interpretable associations. All statistical analyses were performed in Python (version 3.9.21), and the corresponding scripts are provided in Appendix C.

Methods

To enable comparison between events of different magnitude, sediment-related responses were made measurable and comparable by deriving two dimensionless parameters. The use of dimensionless ratios is a common approach in geomorphology and hazard research to account for scale effects and to facilitate cross-event comparisons (Hung et al. 2005; Iverson, 2012):

- **Volume amplification factor (BV):** ratio between the total mudflow volume and the initial outburst water volume, capturing the overall magnitude of sediment entrainment and volume growth along the flow path.
- **Process efficiency parameter (BQ):** ratio between the peak mudflow discharge and the peak outburst discharge, representing the efficiency with which hydrological forcing is converted into sediment mobilisation during downstream propagation.

These parameters are formally defined as:

$$BV = \frac{V_{\text{mudflow}}}{V_{\text{lake}}} \quad (5.4)$$

$$BQ = \frac{Q_{\text{mudflow,peak}}}{Q_{\text{outburst,peak}}} \quad (5.5)$$

Here, V_{mudflow} denotes the total mudflow volume and V_{lake} the released lake water volume. $Q_{\text{mudflow,peak}}$ is the peak discharge of the debris flow, and $Q_{\text{outburst,peak}}$ is the peak outburst discharge at the lake outlet. While BV captures the overall magnitude of volume growth due to sediment entrainment, BQ reflects the dynamic efficiency with which the initial hydrological impulse is transformed into mudflow discharge.

In addition to these response metrics, a composite index was derived to represent the combined influence of sediment availability and valley geometry along the flow path. Composite indices are frequently used to synthesize interacting geomorphological controls where individual parameters cannot be interpreted independently (Hung et al. 2005; Westoby et al. 2014a). The Sediment–Confinement Index (SCI) quantifies the spatial co-occurrence of potentially entrainable sediment sources and valley geometry and is calculated by multiplying the proportion of the flow path classified as V-shaped valley sections by the sum of moraine and landslide sediment shares.

As an initial exploratory step, a Pearson correlation matrix was computed including all hydrological, geomorphometric, sediment and process parameters. The matrix provided a first overview of potential linear relationships and interdependencies among variables. This screening step was used to identify variable pairs showing moderate to strong associations and to avoid redundant testing of highly collinear predictors. Based on this initial assessment, selected variable combinations were subsequently analysed using Spearman rank correlations to evaluate the robustness of monotonic relationships under non-parametric assumptions.

In a second step, dominant controlling factors were identified using an exploratory, data-driven approach. Spearman rank correlations were calculated to assess monotonic relationships between the derived response parameters (BV and BQ) and the candidate controlling variables. Non-parametric correlation measures are well suited for exploratory analyses of geomorphological datasets, which often exhibit non-normal distributions and limited sample sizes (Dubey et al. 2024). Correlations were computed on a pairwise basis, excluding missing values for the respective variable pairs. This analysis served as an exploratory screening to identify parameters showing consistent and physically interpretable relationships across the analysed events and to support the subsequent selection of predictors for statistical modelling.

Results

Table 5.4 provides an overview of the key process and impact characteristics of the analysed GLOF-induced mudflow events in the Ile-Alatau region. The events considered exhibit substantial variation in runout distance, peak discharge, and total mudflow volume. Mudflow volumes range from 150,000 m³ to 5,800,000 m³, while maximum mudflow discharges vary between 30 m³/s and 12,000 m³/s. Runout lengths extend from less than 3 km to nearly 28 km, illustrating pronounced differences in downstream propagation and attenuation behaviour.

Table 5.4.: Process and impact characteristics of the analysed GLOF-derived mudflow events in the Ile-Alatau. The table reports the entrainment ratio, discharge amplification, runout length, total mudflow volume, and peak mudflow discharge for each event. Mudflow volume and peak mudflow discharge values are compiled from published reconstructions (see Appendix A.1 for detailed event-specific references).

Catchment	Glacier	Lake	Dates of outburst	Volume amplification factor (BV)	Process efficiency parameter (BQ)	Runout length [km]	Volume of mudflow [m ³]	Maximum discharge of mudflow [m ³ /s]
Kaskelen	No. 25	No. 16	23.07.1980	7	22	27.9	2,000,000	510
Kaskelen	No. 25	No. 16	05.07.1986	2	8	27.9	220,000	500
Kargaly	Kargalinka	No. 1	23.07.2015	2	8	22.8	150,000	40
Kargaly	Kargalinka	No. 1	14.08.2019	6	6	17.3	1,200,000	30
Ulken Almaty	Kumbel	No. 14	19.08.1975	20	75	17	100,000	300
Ulken Almaty	Sovetov	No. 13	03.08.1977	37	52	15	3,000,000	11,000
Kishi Almaty	Central Tuyksu	No. 2	20.08.1951	10	10	19.5	200,000	500
Kishi Almaty	Central Tuyksu	No. 2	07.08.1956	34	31	24	1,100,000	1,000
Kishi Almaty	Central Tuyksu	No. 2, No. 3	15.07.1973	17	29	9.8	3,800,000	10,000
Talgar	Spotivnyi	No. 7	21.06.1979	4	23	2.7	300,000	340
Talgar	Bezmyannyi	No. 8	06.07.1993	20	133	21.4	2,000,000	2,000
Talgar	Bezmyannyi	No. 8	17.07.2014	6	60	18	300,000	300
Issyk	Zharsay	No. 17	06.07.1958	16	5	14.5	4,000,000	1,000
Issyk	Zharsay	No. 17	07.07.1963	13	15	22	5,800,000	12,000
Issyk	Zharsay	No. 17	03.07.1977	2	28	11.8	830,000	1,100

The calculated BV range between 2 and 37. Lower BV values indicate comparatively limited sediment entrainment relative to the initial lake volume, whereas higher values reflect substantial downstream sediment mobilisation and strong amplification of the initial outburst signal. Events with high BV values are characterised by efficient channel erosion and the mobilisation of additional sediment sources beyond the initial moraine-dammed lake.

Similarly, BQ shows a pronounced spread, ranging from values as low as 5 to values exceeding 130. Low BQ values correspond to events in which peak discharge increases only moderately relative to the initial outburst, whereas high BQ values indicate cases where comparatively modest hydraulic forcing is associated with disproportionately large downstream discharge amplification. Overall, the variability in BV and BQ highlights that neither the initial lake volume nor the peak outburst discharge alone are sufficient to explain the resulting mudflow size or process intensity. Instead, downstream sediment availability and catchment-specific process dynamics appear to exert a decisive control on event magnitude.

Figure 5.4 presents the Pearson correlation matrix for all analysed hydrological, geomorphometric, sediment and process variables. The matrix provides an overview of linear relationships within the dataset and highlights potential interdependencies among controlling factors and response metrics. Strong positive correlations are observed between outburst discharge and peak mudflow discharge ($r = 0.83$), as well as between lake volume and total mudflow volume ($r = 0.62$). In contrast, BV shows only weak linear relationships with most morphometric parameters but moderate positive correlation with landslide sediment share ($r = 0.58$) and moderate negative correlation with V-valley share ($r = -0.43$). These patterns guided the subsequent non-parametric analysis.

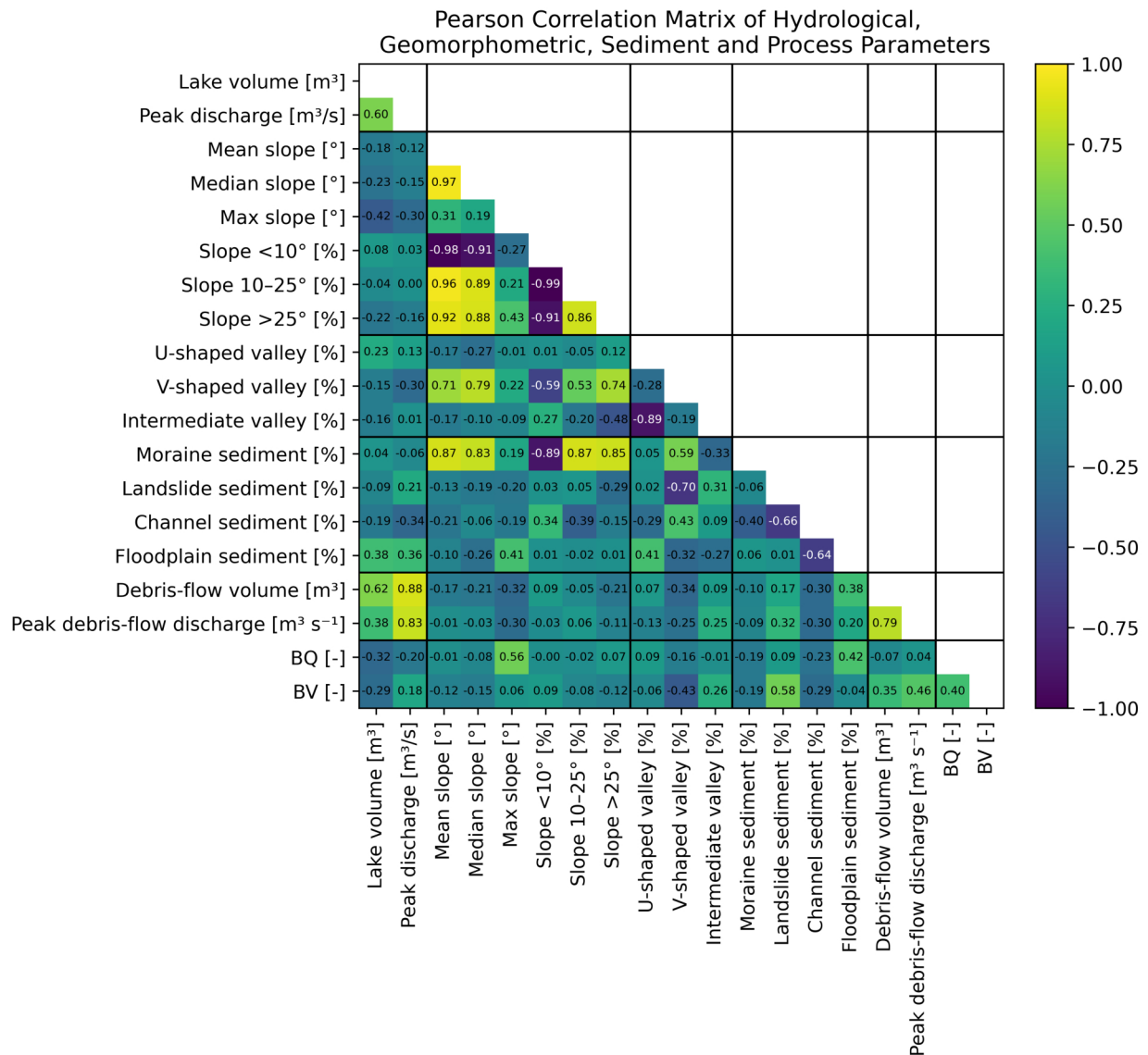


Figure 5.4.: Pearson correlation matrix (r) for hydrological, geomorphometric, sediment, and process parameters of the analysed GLOF-derived mudflow events ($n = 15$). Only the lower triangular matrix is shown. Colours indicate the strength and direction of linear relationships (-1 to +1). The matrix served as an initial exploratory screening to identify dominant associations and potential multicollinearity among variables prior to the subsequent non-parametric Spearman rank correlation analysis.

The results of the exploratory Spearman rank correlation analysis are summarised in Table 5.5. Significant positive correlations are evident between outburst discharge and peak mudflow discharge ($\rho = 0.80$, $p < 0.01$), as well as between lake volume and total mudflow volume ($\rho = 0.71$, $p < 0.01$). These relationships indicate that larger initial hydraulic forcing generally translates into higher absolute discharge and sediment volumes at the event scale.

In contrast, the volume amplification factor BV does not show significant correlations with purely hydraulic variables or with most morphometric parameters. Instead, BV exhibits a significant positive correlation with the proportion of landslide-derived sediments ($\rho = 0.58$, $p = 0.02$), suggesting that catchments with higher contributions from landslide material tend to display stronger volumetric amplification. A moderate positive correlation is also observed between BQ and BV ($\rho = 0.52$, $p = 0.04$), indicating that discharge amplification and volumetric amplification are partially linked. The proportion of V-shaped valley sections shows a moderate negative correlation with BV ($\rho = -0.50$, $p = 0.05$), implying that strongly confined valley geometries may constrain volumetric growth.

For BQ, correlations with geomorphological parameters are generally weak and statistically insignificant. In particular, V-valley share shows only a weak negative relationship with BQ ($\rho = -0.15$, $p = 0.60$). Similarly, SCI displays no statistically significant association with BV. Taken together, these results suggest that while absolute event magnitude is closely linked to initial hydraulic forcing, BV and BQ are more strongly governed by sediment-source characteristics and local process interactions than by individual morphometric control parameters alone.

Table 5.5.: Spearman rank correlation analysis between hydrological, geomorphological, and process-based variables (BV and BQ). Correlation coefficient (ρ), p-value, and sample size are reported.

Variable X	Variable Y	Spearman ρ	p-value	n
Outburst discharge [$\text{m}^3 \text{s}^{-1}$]	Peak mudflow discharge [$\text{m}^3 \text{s}^{-1}$]	0.80	0.00	15
Lake volume [m^3]	Mudflow volume [m^3]	0.71	0.00	15
Median channel slope [$^\circ$]	Volume amplification factor BV [-]	-0.01	0.97	15
Fraction of channel with slope 10-25° [%]	Volume amplification factor BV [-]	0.15	0.60	15
Moraine sediment share [%]	Volume amplification factor BV [-]	-0.15	0.59	15
Landslide sediment share [%]	Volume amplification factor BV [-]	0.58	0.02	15
Channel sediment share [%]	Volume amplification factor BV [-]	-0.20	0.47	15
Process efficiency ratio BQ [-]	Volume amplification factor BV [-]	0.52	0.04	15
Sediment-confinement index (SCI) [-]	Volume amplification factor BV [-]	0.29	0.29	15
V-Valley share [%]	Volume amplification factor BV [-]	-0.50	0.05	15
V-Valley share [%]	Process efficiency ratio BQ [-]	-0.15	0.60	15

Taken together, the correlations for BQ are generally weaker than those observed for absolute discharge and volume relationships. The only statistically significant association is found between BQ and BV ($\rho = 0.52$, $p = 0.04$), indicating that discharge amplification and volumetric amplification are partially coupled. In contrast, geomorphological parameters show no significant relationship with BQ. The proportion of V-shaped valley sections exhibits only a weak negative and statistically insignificant correlation with BQ ($\rho = -0.15$, $p = 0.60$), suggesting that valley confinement alone does not systematically enhance discharge amplification efficiency. Overall, these findings imply that BQ is less directly controlled by individual morphometric parameters and is more strongly influenced by complex local process interactions and event-specific threshold behaviour.

To further assess the robustness of the identified hydrological relationships across event magnitudes, outburst discharge vs. peak mudflow discharge and lake volume vs. mudflow volume were additionally visualised on logarithmic scales (Figure 5.5). The log–log representations illustrate consistent positive scaling relationships across several orders of magnitude, indicating that the observed correlations are not driven by individual extreme events. These results confirm that hydrological forcing constrains absolute impact metrics, while substantial variability remains due to downstream sediment entrainment processes.

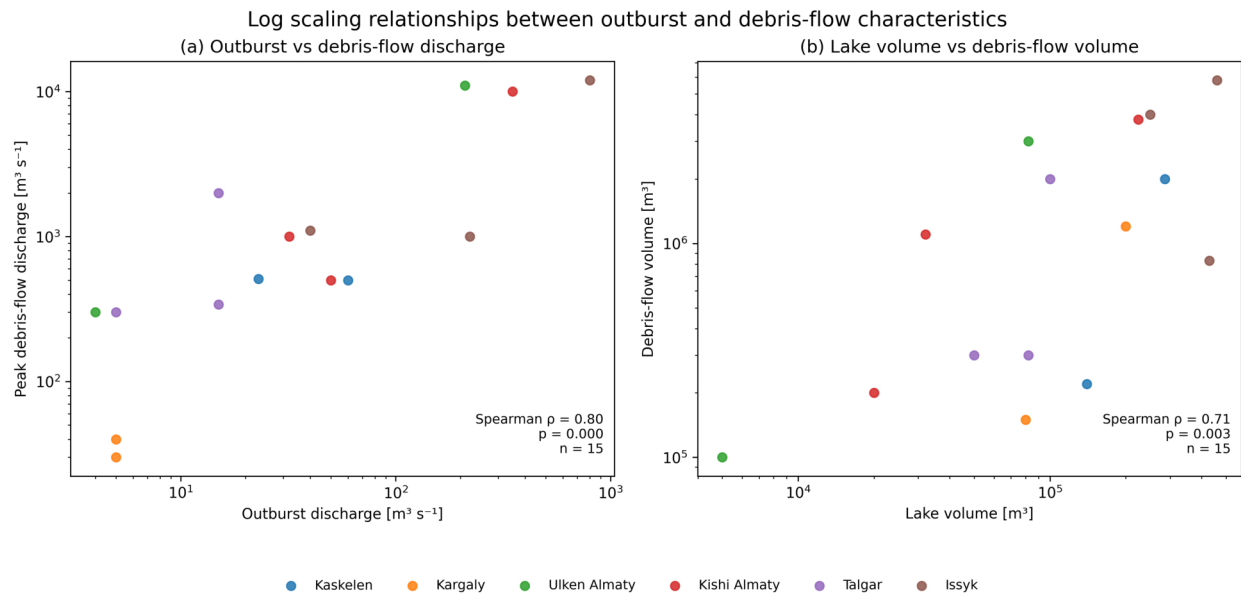


Figure 5.5.: Logarithmic relationships between hydrological forcing and mudflow response for the analysed GLOF events. (a) Peak outburst discharge vs. peak mudflow discharge. (b) Initial lake volume vs. resulting mudflow volume. Both panels show positive scaling across several orders of magnitude, indicating that correlations are not controlled by single extreme events. Colours denote individual catchments (Issyk, Kargaly, Kaskelen, Kishi Almaty, Talgar, Ulken Almaty). Spearman ρ , p -values and n ($=15$) are reported for each panel.

Figure 5.6 illustrates the bivariate relationships and statistical correlations identified in Table 5.5. The complete set of scatterplots and supplementary correlation figures for all analysed variable combinations is provided in Appendix E. Panel (a) shows a clear positive relationship between outburst discharge and maximum mudflow discharge, reflected by a strong and statistically significant correlation ($\rho = 0.80$). Despite some variability between events, higher initial hydraulic forcing generally corresponds to higher peak debris-flow discharge.

Similarly, panel (b) indicates a strong positive association between initial lake water volume and resulting mudflow volume ($\rho = 0.71$). While larger lakes tend to produce larger sediment volumes overall, the scatter also demonstrates that comparatively moderate lake volumes can generate substantial mudflow volumes, highlighting the importance of downstream sediment entrainment processes.

In contrast, the relationship between the sediment-confinement index (SCI) and BV (panel (c)) does not show a clear monotonic pattern and is statistically insignificant ($\rho = 0.29$). This suggests that sediment confinement alone cannot explain volumetric amplification behaviour. Likewise,

panel (d) shows no systematic relationship between V-valley share and BQ ($\rho = -0.15$), indicating that valley geometry, expressed solely as the proportion of V-shaped sections, does not consistently enhance discharge amplification efficiency.

Panel (e) reveals a moderate positive and statistically significant correlation between BQ and BV ($\rho = 0.52$), suggesting that discharge amplification and volumetric amplification are partially coupled but not identical. Overall, the scatterplots emphasise the pronounced variability between events and confirm that BV and BQ capture different, though partly related, aspects of process dynamics, being influenced by distinct combinations of hydrological forcing and sediment availability.

Overview of key hydrological and geomorphic controls on debris-flow amplification

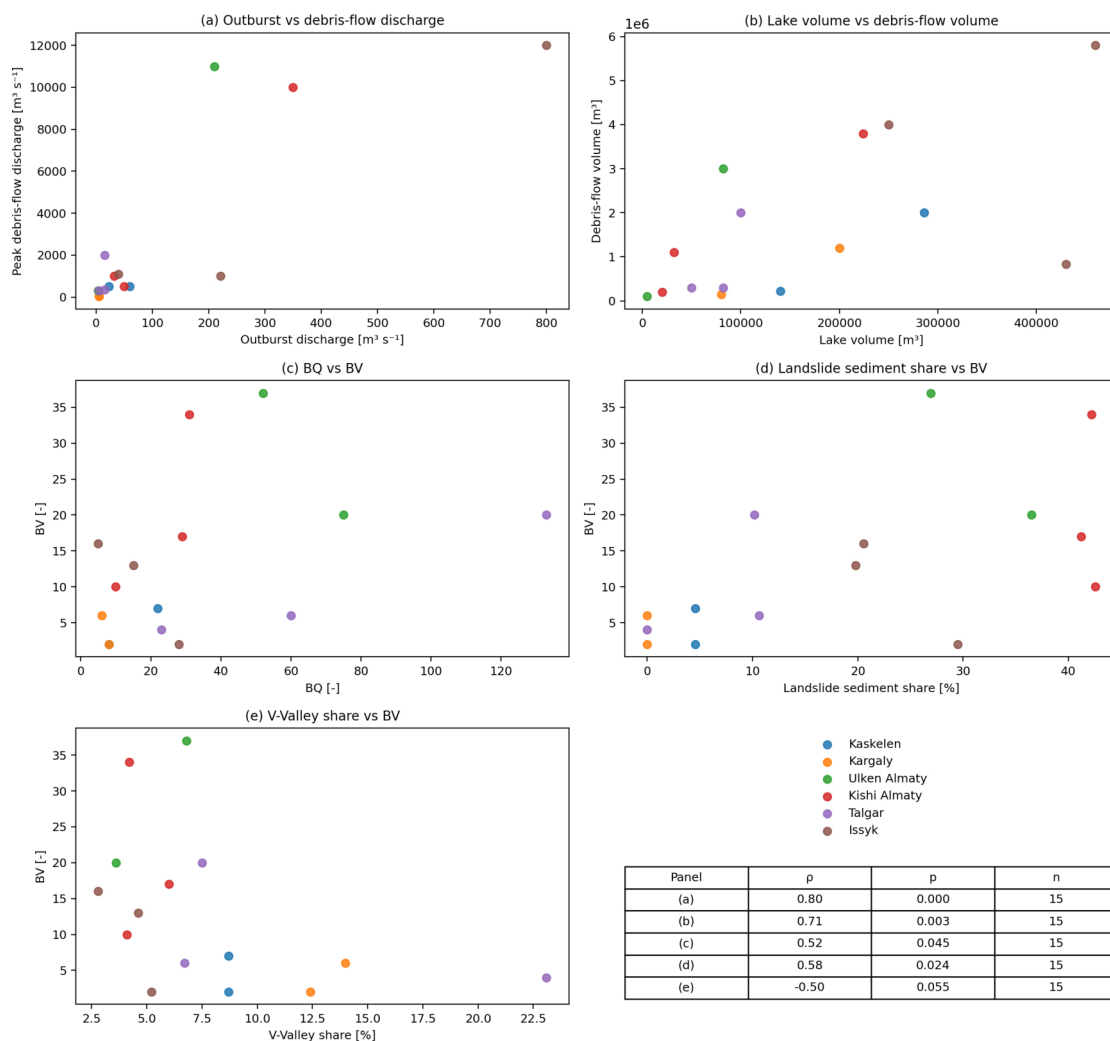


Figure 5.6.: Relationships between hydrological forcing, sediment availability and geomorphic controls and BV for selected GLOF-related mudflows in Central Asia. (a) Peak outburst discharge vs. peak mudflow discharge. (b) Initial lake volume vs. resulting mudflow volume. (c) BQ vs. BV. (d) Landslide sediment share vs. BV. (e) V-valley share vs. BV. Colours indicate individual catchments (Issyk, Kargaly, Kaskelen, Kishi Almaty, Talgar, Ulken Almaty). Spearman rank correlation coefficients (ρ), p-values and sample size ($n = 15$) are summarised in the table.

5.3.2. Baseline Models

Based on the exploratory findings, baseline regression models were formulated to quantify the explanatory power of different groups of controlling factors with respect to volume amplification. These models provide a framework for evaluating more complex interaction effects.

Methods

Based on the exploratory analysis, a subset of parameters was selected for regression modelling to evaluate their explanatory power with respect to variability in BV across events. Predictor selection was guided by statistical evidence from the Spearman rank correlations and conceptual relevance within the process framework outlined in Chapter 4. Particular emphasis was placed on variables that showed consistent and physically interpretable associations with BV.

All regression models were implemented as ordinary least squares (OLS) linear models, which are commonly used in geomorphological studies to assess first-order relationships between process controls and response variables in exploratory settings (Dormann et al. 2013). All models were formulated as linear regressions of the general form

$$BV = \beta_0 + \sum_{i=1}^k \beta_i X_i + \varepsilon, \quad (5.6)$$

where BV denotes the volume amplification factor, β_0 is the intercept, β_i are regression coefficients associated with the explanatory variables X_i , and ε represents the error term capturing unexplained variability.

The candidate predictors were grouped into three conceptual categories reflecting different levels of process control: hydrological forcing at the lake outlet, sediment-source characteristics and geomorphometric controls along the flow path, and process-based coupling metrics that integrate downstream amplification dynamics.

Four baseline model structures of increasing conceptual complexity were formulated to reflect this hierarchical process understanding:

- **M1 (Hydrology):** BV as a function of peak outburst discharge and lake volume.
- **M2 (Hydrology + Sediment source):** BV as a function of peak outburst discharge, lake volume, and landslide-derived sediment share.
- **M3 (Hydrology + Geomorphometry):** BV as a function of peak outburst discharge, lake volume, median channel slope and V-valley share.
- **M4 (Process metric):** BV as a function of peak outburst discharge, lake volume and BQ.

In this framework, landslide sediment share represents a direct proxy for sediment availability along the flow path, which was identified as a significant control in the exploratory analysis. In contrast, BQ is treated as an integrative process metric capturing emergent coupling between hydraulic forcing and sediment mobilisation during downstream propagation, rather than as an independent geomorphic control variable.

This hierarchical structure allows for a systematic evaluation of conceptually nested baseline models. Specifically, M1 (Hydrology) isolates the explanatory power of purely hydrological forcing, M2 (Hydrology + Sediment source) tests the added contribution of sediment-source availability, M3 (Hydrology + Geomorphometry) evaluates geomorphometric modulation, and M4 (Process metric) assesses the added value of an explicit process-based coupling metric (BQ). By comparing these complementary models, the relative importance of forcing, sediment availability, and downstream process dynamics can be assessed.

Table 5.6.: Baseline regression models used to explain variability in BV.

Model	Model name	Predictors	Model formulation
M1	Hydrology	Q_{out}, V_{lake}	$BV = \beta_0 + \beta_1 Q_{out} + \beta_2 V_{lake} + \varepsilon$
M2	Hydrology + sediment source	$Q_{out}, V_{lake}, Sed_{LS}$	$BV = \beta_0 + \beta_1 Q_{out} + \beta_2 V_{lake} + \beta_3 Sed_{LS} + \varepsilon$
M3	Hydrology + geomorphometry	$Q_{out}, V_{lake}, Slope_{med}, V_{valley}$	$BV = \beta_0 + \beta_1 Q_{out} + \beta_2 V_{lake} + \beta_3 Slope_{med} + \beta_4 V_{valley} + \varepsilon$
M4	Process metric	Q_{out}, V_{lake}, BQ	$BV = \beta_0 + \beta_1 Q_{out} + \beta_2 V_{lake} + \beta_3 BQ + \varepsilon$

Results

Table 5.8 summarises the results of the baseline regression models (M1–M4) used to explain variability in BV. The models represent increasing conceptual complexity, from purely hydrological predictors to formulations incorporating sediment-source characteristics, geomorphometric controls and process-based coupling metrics. Given the small sample size ($n = 15$), AIC and BIC values are interpreted cautiously and are used primarily for relative comparison rather than formal model selection.

The purely hydrological model M1 shows moderate explanatory power ($R^2 = 0.293$; adjusted $R^2 = 0.175$), indicating that peak outburst discharge and lake volume together account for a meaningful but limited share of the variability in BV. A substantial proportion of variance remains unexplained, suggesting that hydrological forcing alone is insufficient to capture amplification behaviour.

Incorporating sediment-source availability in model M2 (Hydrology + Sediment) results in a pronounced improvement in model performance ($R^2 = 0.475$; adjusted $R^2 = 0.332$). This model achieves the highest explanatory power as well as the lowest AIC (112.1) and BIC (114.9) values among the baseline models. The results indicate that the proportion of landslide-derived sediments provides substantial additional explanatory power beyond hydrological forcing and represents the strongest single control on BV within the analysed dataset.

Model M3 (Hydrology + Geomorphometry), which includes median channel slope and V-valley share, also improves model performance compared to M1 ($R^2 = 0.454$; adjusted $R^2 = 0.235$). However, its explanatory power and information criteria remain slightly inferior to those of M2, suggesting that geomorphometric conditions contribute to amplification behaviour but exert a weaker control than sediment-source availability.

Model M4 (Process metric), which incorporates the process efficiency parameter BQ, demonstrates moderate explanatory performance ($R^2 = 0.399$; adjusted $R^2 = 0.235$) and achieves an AIC

comparable to M3. This indicates that BQ captures relevant aspects of downstream process coupling between hydraulic forcing and sediment mobilisation. Nevertheless, its performance remains below that of the sediment-source model, reinforcing the dominant role of sediment availability in controlling volume amplification.

Overall, the baseline model comparison demonstrates that BV cannot be explained by hydrological variables alone. Explicit consideration of sediment-source characteristics leads to the strongest improvement in explanatory power, while geomorphometric and process-based metrics provide additional but secondary contributions.

5.3.3. Interaction Effects Models

To account for potential non-additive process interactions, interaction models were developed to test whether the influence of hydrological forcing and process efficiency depends on the geomorphometric conditions encountered along the flow path.

Methods

Interaction models were evaluated to assess whether the influence of sediment availability and process efficiency on BV depends on key geomorphometric conditions along the flow path. Interaction terms were introduced to explicitly represent potential non-additive coupling between controlling factors, reflecting the process-based assumption that sediment entrainment emerges from interacting rather than independent controls (Dormann et al. 2013; Iverson, 2012).

All interaction models were anchored to the baseline hydrological predictors (peak outburst discharge Q_{out} and lake volume V_{lake}) to ensure comparability with the baseline models and to account for first-order hydrological forcing. Landslide-derived sediment share (Sed_{LS}) was included where conceptually required to represent sediment availability.

Based on these conceptual considerations, the following interaction models were fitted:

- **M5a (Sediment availability $\times$ V-valley share):** to test whether the effect of sediment availability on volume amplification depends on valley confinement.
- **M5b (Process efficiency $\times$ slope):** to evaluate whether channel slope modulates the influence of BQ on volume amplification.
- **M5c (Sediment availability $\times$ slope, optional):** to assess whether slope gradient enhances or limits the amplification effect of available sediment sources.

All predictors were mean-centred prior to model fitting to reduce multicollinearity and to facilitate interpretation of interaction terms. Model structures are summarised in Table 5.7.

Results

Of all tested interaction models, M5b (BQ $\times$ slope) exhibits the highest coefficient of determination ($R^2 = 0.578$), indicating the strongest explanatory power among the candidate models. However, the adjusted R^2 (0.261) suggests that part of the explained variance may reflect model complexity relative to the small sample size ($n = 15$). Although M5b does not achieve the lowest AIC or BIC values, it clearly outperforms the baseline process model (M4), highlighting the importance of slope gradient as a modulating factor in the relationship between process efficiency and volume amplification.

Table 5.7.: Interaction models assessing combined effects of hydrological, geomorphometric and sediment-related controls on BV. All predictors were mean-centered prior to model fitting.

Model	Model name	Predictors	Model formulation
M5a	$Sed_{LS} \times V_{valley}$	$Q_{out,c}, V_{lake,c}, Sed_{LS,c}, Conf_c, Sed_{LS,c} \times Conf_c$	$BV = \beta_0 + \beta_1 Q_{out,c} + \beta_2 V_{lake,c} + \beta_3 Sed_{LS,c} + \beta_4 Conf_c + \beta_5 (Sed_{LS,c} \times Conf_c) + \varepsilon$
M5b	$BQ \times Slope$	$Q_{out,c}, V_{lake,c}, Sed_{LS,c}, BQ_c, Slope_c, BQ_c \times Slope_c$	$BV = \beta_0 + \beta_1 Q_{out,c} + \beta_2 V_{lake,c} + \beta_3 Sed_{LS,c} + \beta_4 BQ_c + \beta_5 Slope_c + \beta_6 (BQ_c \times Slope_c) + \varepsilon$
M5c	$Sed_{LS} \times Slope$	$Q_{out,c}, V_{lake,c}, Sed_{LS,c}, Slope_c, Sed_{LS,c} \times Slope_c$	$BV = \beta_0 + \beta_1 Q_{out,c} + \beta_2 V_{lake,c} + \beta_3 Sed_{LS,c} + \beta_4 Slope_c + \beta_5 (Sed_{LS,c} \times Slope_c) + \varepsilon$

The second strongest interaction model is M5a ($Sed_{LS} \times valley$), with $R^2 = 0.527$ and an adjusted R^2 of 0.265. This model indicates that the effect of sediment availability on BV depends on valley morphology. While its AIC and BIC values are not lower than those of the best-performing additive model (M2), the increase in explained variance relative to the hydrology-only and process-only models suggests non-additive interactions between sediment supply and geomorphic confinement.

Table 5.8.: Comparison of baseline and interaction models explaining variability in BV. Models are ranked according to coefficient of determination (R^2), adjusted R^2 , Akaike information criterion (AIC) and Bayesian information criterion (BIC). Lower AIC and BIC values indicate better model performance, while higher R^2 and adjusted R^2 values suggest greater explanatory power.

Model	n	R^2	Adjusted R^2	AIC	BIC
M1: Hydrology	15	0.293	0.175	114.6	116.7
M2: Hydro + Sediment (LS)	15	0.475	0.332	112.1	114.9
M3: Hydro + Geo	15	0.454	0.235	114.7	118.2
M4: Process (BQ)	15	0.399	0.235	114.1	117.0
M5a: $Sed_{LS} \times valley$	15	0.527	0.265	114.5	118.8
M5b: $BQ \times slope$	15	0.578	0.261	114.8	119.8
M5c: $Sed_{LS} \times slope$	15	0.497	0.217	115.5	119.7

Compared to M5a and M5b, M5c shows weaker explanatory power and does not substantially improve model performance relative to its additive counterpart. Overall, the comparison of interaction models indicates that geomorphometric controls, particularly slope gradient and valley confinement, play a significant role in modulating the effects of process efficiency and sediment availability on volume amplification.

To further illustrate these non-additive relationships, bivariate interaction plots of the two strongest models are shown in Figure 5.7. In steep slope classes, BV increases markedly with increasing BQ, whereas the relationship is weaker under low and medium slope conditions (Fig. 5.7b). This pattern supports the statistical interaction observed in M5b and suggests that slope gradient enhances the effectiveness of sediment entrainment processes.

In contrast, the interaction between landslide sediment share and valley confinement (Fig. 5.7a) indicates that sediment availability influences volume amplification differently depending on geomorphic setting. The relationship appears more pronounced in confined valleys, while weaker trends are observed under lower confinement. These visual patterns support the interaction structure identified in M5a.

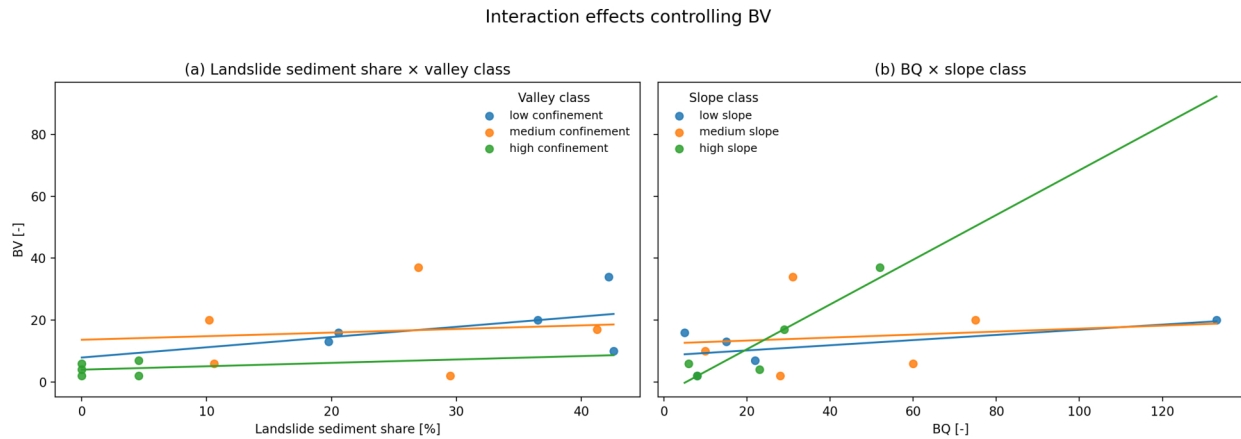


Figure 5.7.: Visualisation of the two strongest interaction models (M5a and M5b). (a) Interaction between landslide sediment share and valley confinement class. (b) Interaction between BQ and slope class. Points represent individual events, and solid lines indicate class-specific linear trends. The relationship between BQ and BV strengthens markedly with increasing slope, whereas the influence of sediment share on BV varies with valley confinement.

5.4. Catchment-Scale Contrasts in Entrainment Behaviour

Figure 5.8 illustrates the distribution of BV and BQ across the investigated catchments in the Ile-Alatau mountain range. The catchments are ordered according to increasing median BV, highlighting systematic differences in entrainment behaviour at the catchment scale.

The lowest BV values occur in Kargaly and Kaskelen, where medians and interquartile ranges are small. Both catchments show comparatively low BQ values with limited variability, indicating consistently low process efficiency and weak volume amplification relative to the triggering discharge.

Talgar and Issyk exhibit intermediate behaviour. In Talgar, BV shows a wide range extending to high values, reflected by a large interquartile range and high maximum values. This variability is mirrored in BQ, which displays the broadest spread of all catchments, including very high individual values. In contrast, Issyk presents moderately elevated BV and BQ values but with a narrower distribution, suggesting more consistent entrainment conditions compared to Talgar.

The highest BV values are observed in Kishi Almaty and Ulken Almaty, where medians and upper ranges exceed those of the other catchments. Both catchments also exhibit elevated BQ values. Ulken Almaty in particular shows consistently high BQ with comparatively limited dispersion, whereas Kishi Almaty demonstrates greater variability across events.

Overall, the boxplots reveal clear contrasts in both the magnitude and variability of BV and BQ between catchments. Catchments with higher median BV tend to exhibit elevated BQ values, although this relationship is not consistent across all catchments, particularly in Talgar where BQ variability is exceptionally high. However, the differing spreads indicate that event-scale variability and local geomorphic conditions likely modulate entrainment dynamics within each catchment.

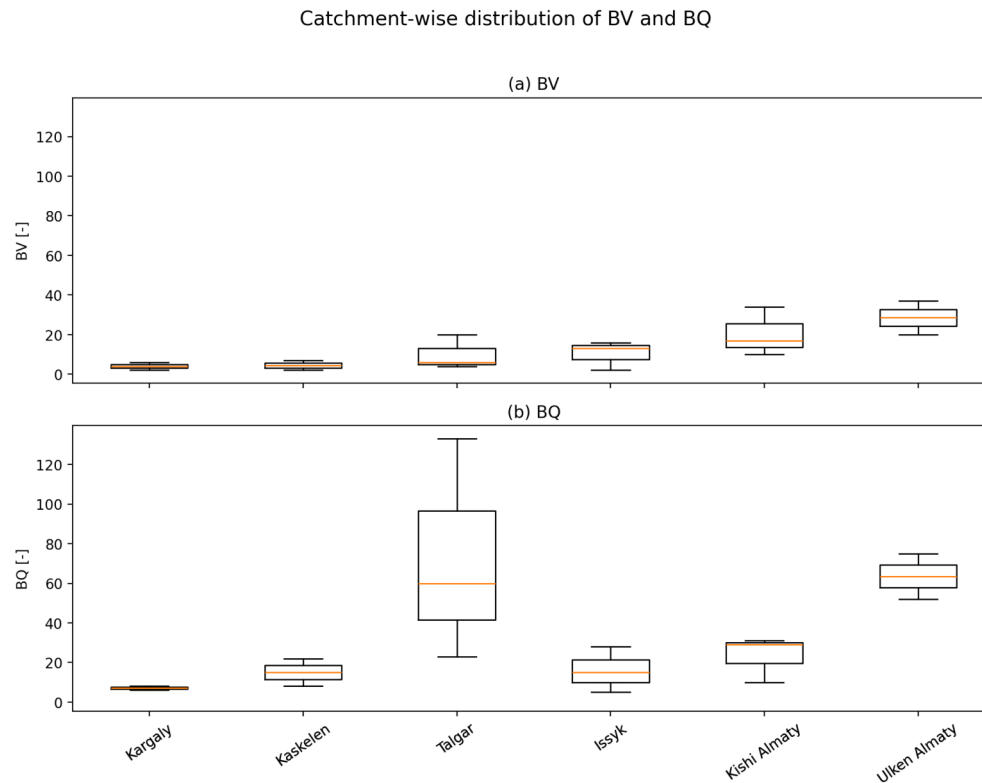


Figure 5.8.: Distribution of (a) BV and (b) BQ across the investigated catchments. The boxplots show the median, the interquartile range and the full data range (whiskers). The catchments are ordered consistently according to the increasing median BV.

5.5. Integrated Synthesis of Process Controls

This integrated synthesis explicitly relates the empirical results to the conceptual expectations outlined in Section 4.5. By comparing observed statistical relationships with the previously identified dominant controls and spatial patterns of entrainment, consistencies and deviations between conceptual expectations and empirical evidence can be assessed.

Across all analysed events, hydrological forcing variables are positively associated with absolute impact metrics. Lake volume correlates positively with mudflow volume, and peak outburst discharge correlates positively with peak mudflow discharge (Table 5.5 and Figure 5.5). However, the baseline regression model using only hydrological predictors (M1) shows only moderate explanatory power for the volume amplification factor BV ($R^2 = 0.293$; Table 5.8), indicating that amplification behaviour cannot be captured by hydrological magnitude descriptors alone.

The two dimensionless response metrics, BV and BQ, exhibit distinct distributions across events and catchments. BV ranges from low amplification values up to strongly amplified events (Table 5.4), while BQ spans from low to very high process-efficiency values. BV and BQ are moder-

ately positively correlated (Spearman $\rho = 0.52$, $p = 0.04$; Table 5.5), but substantial scatter remains across events (Figure 5.6), suggesting that volume amplification and discharge amplification are related but not interchangeable descriptors of process dynamics.

Adding geomorphometric predictors as additive terms improves model performance compared to hydrology-only (M1), but does not outperform the sediment-source model. The additive geomorphometry model (M3) yields $R^2 = 0.454$, whereas the hydrology + sediment-source model (M2) achieves $R^2 = 0.475$ and the lowest AIC and BIC values of all tested models (Table 5.8). This indicates that sediment-source availability (here represented by landslide sediment share) provides substantial explanatory power beyond hydrological forcing, while geomorphometric variables alone show weaker additive effects.

The strongest evidence for geomorphometric modulation emerges when controls are considered jointly through interaction terms. Among the interaction models, the process-efficiency $\times$ slope formulation (M5b: BQ $\times$ slope) achieves the highest R^2 (0.578), while the sediment-availability $\times$ valley-geometry formulation (M5a: SedLS $\times$ valley) provides the second-highest explanatory power ($R^2 = 0.527$; Table 5.8). The corresponding interaction plots (Figure 5.7) show that the relationship between BQ and BV strengthens markedly under steep slope conditions, whereas the influence of landslide sediment share on BV varies with valley confinement. Together, these results support the conceptual expectation that entrainment is governed by coupled controls rather than by independent predictors.

Catchment-scale contrasts further underline systematic differences in entrainment behaviour (Figure 5.8). Catchments with low median BV (Kargaly and Kaskelen) also display low BQ values and narrow distributions. Talgar and Issyk exhibit intermediate amplification behaviour with increased variability, with Talgar showing particularly high and variable BQ. The highest BV values occur in Kishi Almaty and Ulken Almaty, which also tend to show elevated BQ. Overall, catchments with higher BV generally exhibit higher BQ values, but the spreads indicate strong event-to-event variability within catchments.

Regarding valley geometry and sedimentological indicators, the Spearman analysis indicates that relationships are not consistently expressed as simple monotonic trends. V-valley share shows a moderate negative correlation with BV (Spearman $\rho = -0.50$, $p = 0.05$), whereas its association with BQ is weak and statistically insignificant (Spearman $\rho = -0.15$, $p = 0.60$; Table 5.5). The sediment-confinement index (SCI) displays only weak and statistically insignificant association with BV (Spearman $\rho = 0.29$, $p = 0.29$). These results suggest that geomorphometric influences are better captured through interaction structures (e.g., M5a and M5b) than through single-variable monotonic correlations.

Taken as a whole, the integrated empirical results show the following:

1. Hydrological forcing constrains absolute impact metrics, but explains only part of the variability in BV.
2. BV and BQ capture complementary aspects of event behaviour and show strong variability across events and catchments.
3. The highest explanatory power for BV is achieved when BQ is evaluated jointly with geomorphometric controls, particularly channel slope (M5b), and when sediment availability is evaluated jointly with valley confinement (M5a).

6. Discussion

This chapter presents the results of the empirical analysis of sediment entrainment in GLOF-related cascading mass flows, considering existing process-based concepts. The findings are interpreted in terms of the interaction between hydrological forcing, geomorphometric controls, and sediment availability. Particular emphasis is placed on catchment-scale variability, the implications for hazard assessment, and the limitations and prospects of the approach adopted.

6.1. Integration of Controls

The results of this study show that hydrological forcing alone is insufficient to fully explain the magnitude and efficiency of sediment entrainment and the resulting volume amplification in GLOF-related cascading mass flows. Although variables such as initial lake volume and peak discharge exert a strong control on the absolute magnitude of downstream impacts, they do not adequately capture differences in the relative efficiency of sediment mobilisation, as expressed by the entrainment ratio BV. This distinction highlights that large hydrological inputs do not necessarily lead to proportionally high sediment uptake along the flow path.

This finding is consistent with previous studies identifying hydrological parameters as a necessary, though not sufficient condition for intense entrainment processes. Both conceptual and empirical studies of debris flows and outburst-flood-related mass movements emphasise that high discharge and flow velocity provide the energetic precondition for erosion, whereas the actual magnitude of entrainment depends on additional controls acting along the channel network (Hungr et al. 2005; Iverson, 2012; Westoby et al. 2014b). In this context, hydrological forcing primarily governs the overall impact potential, whereas geomorphometric and sedimentological conditions mediate the transformation of a water-dominated flood into a sediment-rich mass flow.

Integrating geomorphometric controls further supports this interpretation. When considered in isolation, individual terrain parameters such as mean slope, valley geometry and relative sediment availability do not exhibit strong monotonic relationships with BV. This suggests that sediment entrainment cannot be described as a simple linear function of a single controlling variable. Rather, the results indicate that entrainment efficiency emerges from the interaction between process efficiency and local terrain characteristics. Although interaction-based behaviour has been widely conceptualised in previous process studies by De Haas et al. (2022), Hungr et al. (2005), and Iverson (2012), there has been limited empirical evidence demonstrating this effect across multiple GLOF-affected catchments (Brüniger, 2023; Meyrat et al. 2024). This study contributes comparative catchment-scale evidence suggesting that entrainment efficiency arises from the interaction between BQ and geomorphometric conditions, rather than from individual controls.

While slope alone does not show a strong additive effect on BV, its interaction with BQ substantially enhances explanatory power, highlighting its role as a geomorphic modulator rather than an independent driver. Steep channel sections do not necessarily lead to high entrainment efficiency by themselves. However, when combined with high BQ, they facilitate effective sediment mobilisation through enhanced shear stresses, channel incision and bank erosion. This interaction-based behaviour lends support to conceptual models in which sediment entrainment is understood as a

process-coupled phenomenon rather than a direct response to static catchment properties (Hungr et al. 2005; Iverson, 2012). From this perspective, geomorphometric conditions modulate the translation of hydrological energy into erosion and sediment uptake rather than acting as independent predictors of entrainment magnitude. By demonstrating that BV is best explained when BQ is interpreted conditional on slope, the results provide catchment-scale empirical support for interaction-based conceptual models of entrainment.

In light of the working hypothesis, the results provide partial support: hydrological forcing constrains absolute impact metrics, but amplification behaviour is best explained when sediment availability and geomorphometric constraints are considered jointly, particularly through interaction structures linking BQ with slope and sediment availability with valley confinement. This dual role — as both an additive predictor and a conditional control in interaction with geomorphometric constraints — underscores that entrainment is facilitated by sediment presence, but its effectiveness depends on terrain configuration and BQ. This finding challenges approaches that implicitly assume dominant single-parameter controls on sediment entrainment and highlights the need for integrated, interaction-based frameworks when analysing and assessing GLOF-related cascading mass flows.

In relation to the first research question, these results demonstrate that sediment entrainment in GLOF-related cascading mass flows cannot be attributed to hydrological forcing or geomorphometric conditions in isolation, but emerges from their interaction along the flow path. By empirically substantiating this interaction at the catchment scale, the study advances current process understanding beyond descriptive or event-specific interpretations.

Beyond the empirical findings, the results can be interpreted within a broader geomorphic systems perspective. The observed interaction effects and threshold-like activation of entrainment sections are consistent with conceptualisations of mountain catchments as non-linear, response-threshold systems, in which process outcomes are governed by the coupling of energy input, sediment supply and spatial connectivity rather than by single deterministic controls (Hungr et al. 2005; Iverson, 1997). In this sense, sediment entrainment in GLOF-related cascading mass flows represents an emergent system response arising from the configuration of hydrological forcing and geomorphometric structure. By empirically demonstrating this behaviour at the catchment scale, the study contributes to a systems-based understanding of GLOF dynamics that extends beyond event-specific interpretations.

6.2. Catchment Variability

The results reveal significant yet consistent differences in entrainment behaviour between the catchments under investigation. These differences are reflected in systematic contrasts in the median, spread and extreme values of BV and BQ. This indicates a reproducible catchment-scale tendency across the available events, rather than a purely event-driven or stochastic outcome. This distinction has rarely been demonstrated empirically in a comparative, multi-catchment setting for GLOF-related cascading mass flows.

Catchments characterised by low BV and BQ values and narrow interquartile ranges show limited variability in entrainment metrics. This pattern indicates relatively stable entrainment behaviour across events and flow-path segments, with sediment mobilisation remaining within a constrained range. This behaviour is consistent with catchments in which entrainment processes are governed by uniform geomorphometric conditions, where flow–sediment interactions respond

gradually to hydrological forcing and systems are either fluvial-dominated or supply-limited (Rickenmann, 1999; Sidle et al. 2023).

In contrast, other catchments exhibit significantly greater dispersion and more pronounced extreme values in BV and BQ. The presence of strong variability and outliers indicates that entrainment is not active throughout the entire flow path, but is instead dominated by the sporadic activation of highly efficient entrainment sections. By systematically contrasting catchments exhibiting low and high variability in entrainment behaviour, this study provides empirical support for distinguishing between relatively stable, supply-limited systems and threshold-dominated catchments characterised by episodic but highly efficient entrainment. Similar threshold-controlled behaviour has been documented in steep, sediment-rich mountain catchments where short reaches can contribute disproportionately to total sediment mobilisation during high-magnitude events (Erokhin et al. 2018; Mergili, Schneider, et al. 2011).

The observed differences between catchments cannot be attributed to a single controlling factor. Instead, the patterns suggest that entrainment variability emerges from the interaction of multiple catchment-scale characteristics. The combination of overall relief structure, the spatial distribution of steep channel sections, and the degree of longitudinal connectivity between sediment sources and the main transport pathway appears particularly important. This comparative, catchment-scale approach builds on previous event- or reach-scale studies by showing how sediment connectivity influences not only the magnitude, but also the variability of entrainment across multiple GLOF-affected catchments. Previous studies have shown that strong connectivity between unstable sediment stores and the channel network promotes non-linear entrainment responses and increases event-to-event variability (Brüniger, 2023; Sidle et al. 2023).

High variability within individual catchments is consistent with heterogeneous internal process spaces, where specific channel or slope sections only become active under particular combinations of hydrological forcing and flow conditions. Moderate events may result in limited entrainment, whereas high-magnitude or rapidly rising discharges can trigger localised but intense erosion and mass entrainment. This type of threshold-driven activation is well documented in cascading mass flows and debris-flow systems (Hungr et al. 2005; Iverson et al. 2011).

Overall, this study advances the current state of knowledge by demonstrating that catchment-scale entrainment variability is not random but reflects systematic differences in geomorphometric organisation and sediment connectivity, leading to distinct and reproducible entrainment signatures across GLOF-affected catchments. Systematic differences between catchments suggest the efficiency and variability of entrainment are emergent properties resulting from the arrangement of topography, sediment availability and connectivity along the flow path. This variability is consistent with conceptual models of GLOF-related cascading mass flows in high-mountain environments, in which sediment entrainment is spatially discontinuous and strongly modulated by threshold behaviour rather than uniform erosion along the channel (Mergili, Schneider, et al. 2011; Rickenmann et al. 2024).

These systematic contrasts directly address the second research question and confirm that sediment entrainment characteristics differ fundamentally between catchments within the Ile-Alatau mountain range. Even under broadly comparable climatic and glaciological conditions, catchment-specific geomorphometric organisation and sediment connectivity lead to distinct entrainment efficiencies and variability patterns.

6.3. Implications for Hazard Assessment

By linking empirical observations with established process-based concepts, the results provide integrative insights into sediment entrainment processes that extend beyond individual events. This integrated perspective supports the interpretation of GLOFs as cascading mass flows and demonstrates the added value of combining empirical analysis with conceptual process understanding for hazard assessment.

The results have direct implications for the assessment of GLOF-related hazards in high mountain catchments. Assessments that focus primarily on initial lake water volume or peak discharge are likely to underestimate the potential magnitude and downstream impact of cascading mass flows. Many studies have demonstrated that sediment entrainment can significantly increase flow volume, density and destructive potential, often surpassing the impact of the initial water release alone (Allen et al. 2016; Hungr et al. 2005; Iverson et al. 2011). This study extends these insights by demonstrating that the degree of hazard amplification depends not only on the availability of entrainable sediment, but on catchment-specific entrainment efficiency, which varies systematically between catchments.

In contrast to approaches that primarily emphasise peak discharge or initial lake volume as primary determinants of downstream impact (Allen et al. 2016; Carrivick & Tweed, 2016), the present findings demonstrate that entrainment efficiency constitutes an independent and systematically varying control at the catchment scale. This shift from source-based magnitude metrics towards efficiency-based transformation potential represents a conceptual advancement in the assessment of GLOF-related hazards.

The observed catchment-specific entrainment signatures show that GLOF initiation conditions that are similar can result in markedly different downstream effects. Catchments with comparable lake volumes and triggering mechanisms may nevertheless exhibit contrasting sediment mobilisation efficiencies, resulting in significant variations in flow transformation, runout distance and impact intensity. This finding aligns with previous observations in steep, sediment-rich mountain regions, where the downstream geomorphometric organisation significantly influences GLOF evolution (Carrivick & Tweed, 2016; Mergili, Schneider, et al. 2011). By empirically demonstrating reproducible differences in entrainment behaviour between catchments, the results provide a process-based explanation for why similar GLOF initiation scenarios can lead to fundamentally different hazard outcomes.

Process-based metrics such as BQ are particularly relevant for hazard assessment, as they capture how efficiently sediment is mobilised along the flow path, rather than focusing solely on the characteristics of the source. High BQ values indicate catchments in which relatively small or moderate releases of water can trigger disproportionate entrainment of sediment and rapid transformation into debris-rich flows. Similar efficiency-based approaches have been identified as essential for enhancing the accuracy of process-based hazard assessments of cascading mass flows (Iverson, 1997; Rickenmann, 1999).

For practical hazard modelling, the results suggest that geomorphometric modulators should be explicitly incorporated into assessment frameworks. Parameters describing slope distribution, valley confinement and the spatial arrangement of steep channel sections are essential for evaluating entrainment potential. Previous modelling studies have emphasised that neglecting such geomorphometric controls can lead to a systematic underestimation of erosion and sediment uptake along

flow paths (Mergili, Schneider, et al. 2011; Sidle et al. 2023). By introducing BQ as an efficiency-based indicator, this study offers a complementary metric for hazard assessment that captures the transformation potential of GLOFs along the flow path, rather than focusing exclusively on source characteristics.

Furthermore, the results suggest that the interaction between controlling factors is particularly significant. The combination of slope characteristics and process efficiency appears to have a greater impact on entrainment behaviour than the parameters considered individually. This finding lends weight to recent calls for hazard models to move beyond single-parameter thresholds and incorporate interacting controls that more accurately reflect the non-linear behaviour of processes in steep mountain catchments (Brüniger, 2023; Sidle et al. 2023). The empirical evidence provided by this study supports this shift by showing that interaction effects between BQ and geomorphic conditions exert a stronger control on entrainment behaviour than individual parameters alone.

At the regional scale, the findings suggest that hazard mapping approaches could be improved by using a differentiated catchment typology. Classifying catchments based on their geomorphic organisation and entrainment behaviour rather than applying uniform discharge or volume thresholds could enable more accurate spatial differentiation of hazard levels. This approach aligns with the concepts of process-based cascading mass flows and has been suggested as a means of reducing uncertainty in regional-scale GLOF hazard assessments (Emmer et al. 2022; Rickenmann et al. 2024). This study provides empirical support for such differentiated, catchment-based approaches by demonstrating that entrainment efficiency and variability are emergent properties of catchment organisation, which can be used to prioritise hazard-prone catchments beyond simple volume-based criteria. Overall, this study advances GLOF hazard assessment by shifting the focus from source-based magnitude metrics to catchment-scale entrainment efficiency, providing an empirically grounded basis for process-oriented, differentiated hazard evaluation in high-mountain environments.

6.4. Methodological Limitations and Uncertainties

This study is subject to several limitations relating to data availability, methodological constraints, and process representation. Firstly, the small number of documented GLOF-related cascading mass flow events available for analysis ($n = 15$) means that the level of statistical robustness required for strictly predictive modelling cannot be achieved. However, this study explicitly aims to identify dominant process controls and recurring entrainment patterns at the catchment scale, rather than predict individual events. The consistency of the observed relationships across multiple catchments suggests that the identified patterns reflect systematic processes rather than event-specific anomalies.

A further limitation arises from the nature of the historical event data. Estimates of water volume, peak discharge and mobilised sediment volumes are subject to considerable uncertainty, as most events were reconstructed retrospectively using indirect evidence. Such uncertainties are inherent to natural hazard research in high-mountain environments and primarily affect the reliability of absolute entrainment metrics (Carrivick & Tweed, 2016; Emmer et al. 2022). By adopting a comparative and relative analytical framework, this study reduces the influence of absolute errors and enables robust inter-catchment contrasts in entrainment behaviour to be identified.

Rather than being quantified volumetrically, sediment availability along the flow path was assessed qualitatively and in relative terms. This approach reflects both data limitations and the inherent difficulty of reconstructing the spatial distribution of sediment stores for historical events. Importantly, previous studies demonstrate that relative sediment availability, connectivity and geomorphometric context are often more informative for understanding entrainment dynamics than absolute sediment volumes, particularly in steep, supply-rich catchments (Rickenmann et al. 2024). Within this context, the adopted approach is well suited to capture spatial contrasts in entrainment potential.

From a methodological perspective, the application of linear statistical models represents a simplification of inherently nonlinear and threshold-controlled processes. Sediment entrainment in cascading mass flows is governed by complex feedbacks between flow hydraulics, channel deformation and sediment mobilisation, which cannot be fully represented by linear relationships (Hungar et al. 2005; Iverson, 1997). Nevertheless, linear models provide a transparent and interpretable framework for isolating dominant controls and first-order relationships at the catchment scale, which is the primary focus of this study.

In addition to the uncertainties inherent in the reconstruction of historical events, the derivation of parameters introduces further sources of uncertainty. Geomorphometric variables, such as mean slope, valley confinement and connectivity metrics, are derived from DEMs and flow-path delineations, which are sensitive to spatial resolution, data quality, and methodological choices. For example, variations in DEM resolution or channel extraction thresholds may influence the calculated slope distribution and the representation of steep reaches, thereby affecting the interpretation of interaction effects. Similarly, the qualitative classification of sediment availability along the flow path involves subjectivity, especially when field evidence is incomplete or geomorphic signatures are obscured. Although BV and BQ were calculated consistently across all catchments, uncertainties in the input parameters inevitably propagate into these indices. However, as the analysis adopts a comparative and internally consistent framework, relative differences between catchments are considered to be more robust than absolute metric values. Nevertheless, future work should explicitly assess parameter sensitivity in order to better quantify the influence of input uncertainty on entrainment indicators.

Large-scale field experiments in Kazakhstan, such as those conducted in the Chemolgan catchment, demonstrate that small-scale or simplified experimental setups are insufficient to reproduce the behaviour of natural debris flows, particularly with respect to coarse material mobilisation and channel evolution (Rickenmann et al. 2024). The authors emphasise that only experiments at a scale close to 1:1 allow the development of high-density flows and realistic entrainment dynamics. Such experimental conditions are rarely achievable for historical GLOF events, including those analysed in this study, highlighting the necessity of alternative empirical approaches for process-oriented investigations.

Furthermore, sediment entrainment is a strongly path-dependent process controlled by local channel morphology, transient erosion–deposition patterns and feedback mechanisms between flow and bed material (Mergili, Schneider, et al. 2011; Sidle et al. 2023). Event-integrated indicators such as BV and BQ alone cannot fully capture these dynamics. However, as integrative proxies they provide complementary and robust measures of overall entrainment behaviour and are well suited to comparative, catchment-scale analyses aimed at identifying dominant process controls rather than reproducing exact event dynamics.

The transferability of the findings should therefore be interpreted with caution. The identified interaction patterns and efficiency-based entrainment behaviour are most directly applicable to steep, sediment-rich, supply-abundant high-mountain catchments comparable to the Ile-Alatau setting. In low-gradient, sediment-limited or heavily engineered systems, different dominant controls may prevail. Future comparative studies across contrasting geomorphic environments are required to evaluate the broader applicability of the proposed interaction-based framework.

6.5. Outlook for Future Research

The findings of this study emphasise the importance of future research approaches that explicitly address the dynamic and spatially distributed nature of sediment entrainment in cascading mass flows. An important next step is to expand the empirical database by including additional documented GLOF events across Central Asia. A larger, more diverse set of events would enable a more robust assessment of variability at the catchment scale and improve the generalisability of identified entrainment patterns beyond the Ile-Alatau region.

Future research would benefit from integrating high-resolution topographic data to capture localised entrainment zones and channel-scale geomorphic changes more effectively. Techniques such as airborne Light Detection and Ranging (LiDAR), Unmanned Aerial Vehicle (UAV)-based surveys and Structure from Motion (SfM) photogrammetry can quantify erosion and deposition patterns at a high spatial resolution, even in steep and remote terrain (James et al. 2017; Westoby et al. 2012). Conducting repeated pre- and post-event surveys could substantially improve sediment mobilisation reconstruction and provide spatially explicit constraints on entrainment processes that cannot be obtained through event-integrated metrics alone.

Another promising direction for future work is to combine empirical, event-based analyses with process-based, numerical modelling. Physically based models that explicitly simulate erosion, sediment transport and flow–bed feedback could be used to test the identified interactions mechanistically, such as the combined influence of slope characteristics and process efficiency. High-resolution, reach-scale simulations approaching 1:1 conditions could provide a more realistic representation of channel deformation, sediment availability and evolving entrainment behaviour, consistent with the findings of the Chemolgan large-scale field experiments (Rickenmann et al. 2024).

Targeted field monitoring in selected catchments of the Ile-Alatau could further improve our understanding of the processes involved. Repeated cross-sectional surveys, sediment budget assessments and flow velocity measurements during high-magnitude events would enable the direct validation of conceptual entrainment models and enhance the transferability of empirical relationships between hydrological forcing, geomorphometric controls and sediment mobilisation characteristics (Mergili, Schneider, et al. 2011; Sidle et al. 2023).

Finally, future research could focus on developing simple, process-based indices that summarise key entrainment controls for use in regional hazard assessments. These indices would be based on empirical observations but informed by an understanding of processes. They could provide a practical link between detailed scientific analyses and operational hazard mapping. This would support more differentiated, catchment-specific evaluations of GLOF-related risk and help bridge the gap between process understanding and operational hazard assessment. Practically, this implies that catchments with steep, confined reaches and high inferred process efficiency should be prioritised for detailed scenario modelling and monitoring, even where source-lake volumes are moderate.

7. Conclusion

Sediment entrainment is a key process that controls the evolution, magnitude and impact of GLOFs in high mountain environments. This thesis investigated sediment entrainment in GLOF-related cascading mass flows in the Ile-Alatau mountain range in south-eastern Kazakhstan by combining a literature-based conceptual framework with an empirical, catchment-scale analysis of documented events. The aim was to identify the dominant hydrological, geomorphometric and sedimentological factors controlling sediment entrainment, and to evaluate how these factors vary between catchments.

7.1. Key Findings

RQ1: Which hydrological, geomorphometric and sedimentological factors and their interactions influence sediment entrainment in cascading mass flows following GLOFs in the Ile-Alatau mountain range? The results demonstrate that sediment entrainment emerges from the combined influence of hydrological forcing, sediment availability and geomorphometric conditions along the flow path. Hydrological forcing constrains the absolute magnitude of events, but alone does not explain variability in amplification behaviour. Sediment availability provides a necessary but not sufficient additive control on volume amplification, indicating that the presence of entrainable material is a primary prerequisite for substantial downstream growth. However, geomorphometric conditions determine how effectively this sediment can be mobilised. In particular, interaction structures between BQ and slope highlight that steep channel sections enhance entrainment efficiency when high process intensity is present. Similarly, valley confinement modulates the effect of sediment availability, indicating that terrain configuration governs the spatial efficiency of sediment mobilisation. While high discharge and flow energy provide the capacity for erosion, lake volume and outburst mechanisms alone are insufficient predictors of downstream process magnitude. Instead, entrainment behaviour reflects a non-linear interaction between forcing, sediment presence and geomorphometric constraints.

RQ2: How do sediment entrainment characteristics and their controlling hydrological and geomorphological factors differ between individual catchments within the Ile-Alatau mountain range? Despite comparable climatic and glaciological settings, systematic contrasts in entrainment behaviour were identified between catchments. Those with steeper longitudinal profiles, narrower valley sections and greater spatial connectivity of sediment stores along the flow path exhibit more intense and sustained entrainment, rapidly transforming water-dominated floods into debris-rich flows. Conversely, catchments with wider valley floors or early deposition zones demonstrate limited entrainment. These differences emphasise the significance of catchment-specific geomorphological configurations in controlling GLOF evolution.

RQ3: What insights can be derived from an integrated empirical and conceptual analysis of documented GLOF events in the Ile-Alatau region regarding sediment entrainment processes and their dominant hydrological and geomorphometric controls? The combined conceptual and empirical approach confirms that sediment entrainment follows a systematic, zoned pattern along the flow path, with distinct initial, transit and deposition zones. The most

effective sediment mobilisation occurs in the upper to middle reaches, where high flow energy coincides with plentiful sediment sources. This process-based understanding reinforces the concept of GLOFs as cascading mass flows rather than purely hydrological flood events, emphasising the need to consider the processes that occur downstream in hazard assessments.

Overall, the results partially support the working hypothesis. Sediment entrainment in GLOF-related cascading mass flows is governed by interactions between hydrological forcing and geomorphometric conditions, while sediment availability acts both as a direct additive control on volume amplification and as a conditional modulator through its interaction with terrain configuration. However, the findings do not support a simple linear control by individual parameters, highlighting the importance of non-linear, interaction-based process dynamics.

7.2. Implications

These findings have important implications for the assessment of GLOF hazards, numerical modelling and risk management practices. If downstream sediment entrainment is not explicitly considered, hazard assessments that focus primarily on glacial lake characteristics and potential outburst volumes risk systematically underestimating event magnitude. Incorporating geomorphometric controls and sediment availability at the catchment scale can substantially improve estimates of runout distance, flow type and impact severity.

For modelling applications, the results highlight the importance of incorporating sediment entrainment processes into GLOF and debris-flow simulations. Models that assume constant flow volumes or neglect erosion–deposition dynamics are unlikely to reproduce the behaviour of observed events in sediment-rich, steep mountain catchments such as the Ile-Alatau. The conceptual framework developed in this study provides a basis for parameterising entrainment processes in future numerical modelling efforts, particularly in models that explicitly simulate erosion–deposition coupling and flow–bed feedback mechanisms.

From a practical perspective, the significant impact of catchment-specific conditions indicates that regional hazard management strategies should move beyond uniform classification systems towards site-specific, process-based evaluations. This is particularly relevant in the Ile-Alatau region, where the proximity of glacierised headwaters to densely populated valleys exacerbates the impact of sediment-rich mass flows.

7.3. Final Remarks

This thesis demonstrates that sediment entrainment is a dominant control on the dynamics and downstream impact of GLOF-related mass flows in Central Asia. By explicitly linking hydrological forcing, geomorphometry and sediment availability at the catchment scale, the thesis contributes to a more process-oriented understanding of GLOFs. It also provides a foundation for improved hazard assessment and modelling in the context of ongoing climate change.

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Appendix

A. Overview of GLOF Events

A.1. Event Database

Table 7.1.: Compilation of documented GLOF events used for the analysis, including event characteristics, location, and associated references.

Catchment	Glacier	Lake	Dates of outburst	Lake Type	Lake Longitude	Lake Latitude	Height Lake [m a.s.l.]	Outburst Mechanism	Documented GLOF Driver	Catchment area [km ²]	Lake volume [m ³]	Peak outburst discharge [m ³ /s]	Volume of mudflow [m ³]	Maximum discharge of mudflow [m ³ /s]	Reference
Kaskelen	No. 25	No. 16	23.07.1980	Moraine dammed	76.601807	42.923032	3425	Subglacial tunnel	glacier & snow melt over several years	296	286,000	23	2,000,000	510	1,3,4,5,9
Kaskelen	No. 25	No. 16	05.07.1986	Moraine dammed	76.601807	42.923032	3425	Subglacial tunnel	glacier & snow melt over several years	296	140,000	60	220,000	500	1,3,5,9,10
Kargaly	Kargalinka	No. 1	23.07.2015	Moraine dammed	76.847391	43.00693	3523	Subglacial tunnel	High temperatures	46	80,000	5	150,000	40	2,3,5,7,9,10,11
Kargaly	Kargalinka	No. 1	14.08.2019	Moraine dammed	76.847391	43.00693	3523	Subglacial tunnel	artificial emptying	46	200,000	5	1,200,000	30	2,3,9,10
Ulken Almaty	Kumbel	No. 14	19.08.1975	Supraglacial	77.043572	43.060202	3460	overtopping and Moraine collapse	high temperature =>glacier melt	273	5,000	4	100,000	300	1,3,5,7,8,10
Ulken Almaty	Sovetov	No. 13	03.08.1977	Moraine dammed	77.031527	43.044088	3380	Moraine collapse	high temperature =>glacier melt	273	82,000	210	3,000,000	11,000	1,2,3,4,5,7,8,10
Kishi Almaty	Central Tuyksu	No. 2	20.08.1951	Moraine dammed	77.082339	43.066034	3382	Subglacial tunnel	high temperature & moistening the moraine due to infiltration	125	20,000	50	200,000	500	1,2,3,5,7,9,10
Kishi Almaty	Central Tuyksu	No. 2	07.08.1956	Moraine dammed	77.082339	43.066034	3382	Subglacial tunnel	high temperature => glacier & snow melt and rapid thawing of the soil in the upper moraine layer	125	32,000	32	1,100,000	1,000	3,5,10
Kishi Almaty	Central Tuyksu	No. 2, No. 3	15.07.1973	Moraine dammed	77.082339	43.066034	3374	Subglacial tunnel	high temperatures & intense rainfall	125	224,000	350	3,800,000	10,000	1,2,3,4,5,7,8,9,10
Talgar	Spotivnyi	No. 7	21.06.1979	Moraine dammed	77.32267	43.156408	3230	Subglacial tunnel	glacier & snow melt over several years	472	82,000	15	300,000	340	1,2,3,4,5,9,10
Talgar	Bezmyannyi	No. 8	06.07.1993	Moraine dammed	77.270543	43.14588	3385	Subglacial tunnel	glacier & snow melt over several years	472	100,000	15	2,000,000	2,000	1,2,3,4,5,9,10
Talgar	Bezmyannyi	No. 8	17.07.2014	Moraine dammed	77.276701	43.14449	3385	Subglacial tunnel	glacier & snow melt over several years	472	50,000	5	300,000	300	1,2,3,5,9,10
Issyk	Zharsay	No. 17	06.07.1958	Moraine dammed	77.42	43.16	3380	Subglacial tunnel	precipitation, lake rupture, and a combination of these factors	267	250,000	221	4,000,000	1,000	5,7,9,10
Issyk	Zharsay	No. 17	07.07.1963	Moraine dammed	77.42	43.16	3380	Subglacial tunnel	heavy warm rain and thunderstorms	267	460,000	800	5,800,000	12,000	1,3,5,6,7,8,9,10
Issyk	Zharsay	No. 17	03.07.1977	Moraine dammed	77.42	43.16	3380	Subglacial tunnel	high temperature =>glacier & snow melt	267	430,000	40	830,000	1,100	1,4,9,10

¹ Medeu et al. (2016)

² Medeu et al. (2020)

³ Medeu et al. (2022)

⁴ Popov et al. (2024)

⁵ Popov et al. (2025)

⁶ Yafyazova (2007)

⁷ Yafyazova (2011)

⁸ Rickenmann et al. (2024)

⁹ Lützow et al. (2023)

¹⁰ Shrestha et al. (2023)

¹¹ NASA (2015)

A.2. Event-Specific Documentation

Kaskelen, Glacier No. 25, Lake No. 16, 23.07.1980

On 23 July 1980, a large glacial debris-flow event occurred in the Kaskelen catchment in the northern Tien Shan. The event is classified as a GLOF-coupled mud-and-rock debris flow and represents one of the most significant documented debris-flow events in the Kaskelen valley. In terms of process dynamics, it is comparable to the Talgar event of 1979, although its overall magnitude was somewhat lower. The event is characterised by a relatively small initial water release that triggered extremely efficient downstream sediment entrainment, resulting in a debris flow of catastrophic proportions (Medeu et al. 2016).

The source area was located in the high-mountain section of the Kaskelen valley at elevations of approximately 3,200-3,500 m above sea level. The initiating water body was a small moraine-dammed glacial lake (Lake No. 16) situated on the moraine of a small hanging glacier within a glacier-moraine complex that had been identified as potentially unstable prior to 1980. The lake had remained largely empty for an extended period before rapidly refilling due to blockage of submoraine drainage pathways (Medeu et al. 2016).

Meteorological conditions preceding the event were characterised by persistently high air temperatures and strong solar radiation in mid to late July 1980. No exceptional rainfall event was documented as a primary trigger. Instead, intense glacier melt led to increased inflow into the lake and a rapid rise in lake level. The moraine dam consisted of loosely consolidated blocky, gravelly and fine-grained material with locally ice-rich sections, favouring internal erosion processes under increasing hydrostatic pressure (Medeu et al. 2016).

The event was initiated by the sudden opening of a previously existing intramoraine drainage conduit on 23 July 1980, resulting in the rapid partial to near-complete drainage of the glacial lake. Internal erosion processes such as piping and suffosion, combined with progressive structural weakening of the moraine body due to elevated water pressure, are considered the dominant failure mechanisms. The released lake-water volume was relatively small, with a maximum lake volume of approximately 280,000 m³, indicating that the initial GLOF alone was insufficient to explain the subsequent magnitude of the debris flow (Medeu et al. 2016).

The initial outburst generated a flood-dominated flow that rapidly propagated downstream and transformed into a dense mud-and-rock debris flow through intense bed and bank erosion and the entrainment of large volumes of moraine and valley-fill material (Medeu et al. 2016). The released lake-water volume was relatively small, with a maximum lake volume of approximately 286,000 m³ and an estimated peak outburst discharge of about 23 m³/s. Downstream, sediment entrainment strongly amplified the flow, producing a reconstructed maximum debris-flow discharge of approximately 510 m³/s and a total mudflow volume of about 2,000,000 m³ (Medeu et al. 2016).

Mean flow velocities are estimated at approximately 3-5 m/s, with locally higher velocities in steep channel reaches. The debris flow transported very coarse material, including multi-metre boulders, and exhibited a bulk density on the order of 2,300-2,400 kg/m³, indicating extremely high shear stresses and transport capacity (Medeu et al. 2016). Based on the compiled reconstructions, the total mudflow volume is approximately 2,000,000 m³ (Medeu et al. 2016).

The debris flow traversed the upper and middle reaches of the Kaskelen valley and caused widespread destruction along its path. Bridges, road sections, channel structures and industrial facilities were severely damaged or completely destroyed, and human casualties were reported. Owing to its extreme sediment entrainment efficiency and large downstream impact, the 1980 Kaskelen event represents a key reference case for GLOF-related debris-flow hazards in the northern Tien Shan and clearly demonstrates that relatively small glacial lakes can trigger catastrophic debris flows when connected to highly erodible valley systems (Medeu et al. 2016).

Kaskelen, Glacier No. 25, Lake No. 16, 05.07.1986

On 5 July 1986, a large glacial debris-flow event occurred in the Kaskelen catchment in the northern Tien Shan. The event is classified as a GLOF-coupled mud-and-rock debris flow and represents one of the significant debris-flow events affecting the Kaskelen valley during the 1980s. Although its overall magnitude was lower than that of the catastrophic 23 July 1980 event, the 1986 debris flow confirms the continued instability of glacier-moraine systems in the region well beyond the 1970s and highlights the persistence of glacially controlled hazards (Medeu et al. 2016).

The source area was located in the high-mountain section of the Kaskelen valley at elevations of approximately 3,200-3,500 m above sea level. The initiating water body was a moraine-dammed glacial lake situated within the same alpine glacier-moraine system that had generated earlier debris flows in the catchment. Compared to the largest reference events in neighbouring valleys, the lake involved in the 1986 event was relatively small, providing only a limited initial water volume (Medeu et al. 2016).

Meteorological conditions preceding the event were characterised by sustained early-summer warming and strong solar radiation in late June and early July 1986. No exceptional rainfall event was documented as a primary trigger. Instead, intensified glacier melt led to increased inflow into the lake and a progressive rise in lake level. The moraine dam consisted of loosely consolidated blocky, gravelly and fine-grained material with locally ice-rich sections, making it susceptible to internal erosion under elevated hydrostatic pressure (Medeu et al. 2016).

The event was initiated by the sudden partial drainage of the glacial lake on 5 July 1986. Internal erosion processes, including piping and suffosion within the moraine body, combined with increasing water pressure, are considered the dominant failure mechanisms (Medeu et al. 2016). The maximum lake volume prior to outburst is estimated at approximately 140,000 m³, with a peak outburst discharge of about 60 m³/s (Medeu et al. 2016).

Following the lake outburst, a flood-dominated flow developed in the upper channel sections and rapidly transformed into a dense mud-and-rock debris flow through intense bed and bank erosion and the entrainment of unconsolidated moraine and valley-fill material. This transformation occurred already in the upper and middle reaches of the Kaskelen valley. The debris flow propagated downstream in surge-like waves with a high solid fraction and block-rich fronts, reflecting efficient sediment entrainment and transport (Medeu et al. 2016).

Reconstructed peak discharges increased markedly downstream as a result of sediment entrainment and channel erosion. Maximum debris-flow discharge reached approximately 500 m³/s,

while the total mudflow volume is estimated at about 220,000 m³. Mean flow velocities are estimated at approximately 3-5 m/s, with locally higher values in steeper channel reaches (Medeu et al. 2016).

The debris flow transported coarse moraine and slope material, including large blocks, and exhibited a high bulk density indicative of a dense mud-and-rock flow. The total volume of deposited sediment is estimated to be on the order of several hundred thousand cubic metres and clearly below 1,000,000 m³. Deposition occurred predominantly in the upper and middle reaches of the Kaskelen valley, accompanied by a progressive loss of flow energy downstream (Medeu et al. 2016).

The event caused damage to infrastructure, including bridges, road sections and channel structures, while settlement areas were only locally affected. No fatalities were reported. Overall, the 5 July 1986 Kaskelen debris flow represents a substantial but sub-extreme GLOF-related event that demonstrates how relatively small glacial lakes can trigger hazardous debris flows when combined with efficient downstream sediment entrainment, albeit with a significantly lower impact than the catastrophic 1980 event (Medeu et al. 2016).

Kargaly, Kargalinka Glacier, Lake No. 1, 23.07.2015

On 23 July 2015, a significant glacially influenced mud-and-rock debris-flow event occurred in the Kargaly catchment on the northern slope of the Trans-Ili Alatau, affecting the western outskirts of Almaty. The event originated in the high-mountain zone of the catchment and is widely documented in the scientific literature as a modern reference case of glacial debris-flow activity in the region (Medeu et al. 2019; Shahgedanova et al. 2024).

The triggering conditions were characterised by persistently elevated summer air temperatures and enhanced glacier and snowmelt, leading to increased meltwater availability within the glacier-moraine system. No evidence exists for an exceptional short-duration precipitation event as the primary trigger. Instead, the debris flow is interpreted as being initiated by the sudden drainage of a small moraine- or intramoraine water body, followed by rapid downstream transformation driven by intense bed and bank erosion (Medeu et al. 2019; Shahgedanova et al. 2024).

The initial water-dominated release generated a flood wave that quickly entrained large volumes of unconsolidated moraine and channel material in the steep upper reaches of the Kargaly valley, leading to a rapid transformation into a dense mud-and-rock debris flow with a high solid fraction (Medeu et al. 2019). Quantitative reconstructions indicate a total mudflow volume of approximately 150,000 m³ and a maximum debris-flow discharge of about 40 m³/s, although volume estimates can vary between studies due to differences in reconstruction approaches (Popov et al. 2024).

The debris flow propagated downstream towards the Kargaly debris-flow retention dam, where a substantial portion of the solid material was retained. This significantly reduced the destructive impact on downstream urban areas, although overtopping water and subsequent releases contributed to secondary erosion and redeposition of debris on the alluvial fan. The event caused considerable damage to residential buildings, roads and local infrastructure in the lower catchment, but no fatalities were reported (Medeu et al. 2019; Mussina et al. 2023).

In a regional context, the 23 July 2015 Kargaly debris flow is recognised as part of an increased frequency of glacially influenced debris-flow events in the Trans-Ili Alatau during the late 20th and early 21st centuries. Multiple studies identify this event as being closely linked to long-term climatic warming, enhanced glacier melt and increasing instability of glacier-moraine systems, rather than to short-lived meteorological extremes (Medeu et al. 2019; Shahgedanova et al. 2024; Sydyk et al. 2025).

Kargaly, Kargalinka Glacier, Lake No. 1, 14.08.2019

On 14 August 2019, a glacial-hydrological disturbance occurred in the Kargaly catchment on the northern slope of the Trans-Ili Alatau. The event is documented in recent regional debris-flow and GLOF databases as a small-volume glacial water-release episode associated with instability within a moraine-lake system, rather than as a fully developed destructive debris flow (Shahgedanova et al. 2024).

The disturbance originated in the high-mountain zone of the Kargaly basin and was linked to rapid internal drainage of a small moraine-dammed or intramoraine lake. Hydro-climatic analyses indicate that sustained summer warming and enhanced glacier melt acted as the dominant preconditioning factors, promoting increased meltwater input and the activation or enlargement of internal drainage pathways within the moraine body. No exceptional short-duration precipitation event is identified as a primary trigger (Iskaliyeva et al. 2025; Sydyk et al. 2025).

The event is associated with artificial emptying and/or controlled drainage operations within the moraine-lake system. In the compiled event reconstruction, the estimated lake volume prior to outburst was approximately 200,000 m³, while the peak outburst discharge is reported as about 5 m³/s. Despite the low peak outburst discharge, downstream sediment entrainment and channel erosion led to a substantial debris-flow response, with a reconstructed mudflow volume of approximately 1,200,000 m³ and a maximum mudflow discharge of about 30 m³/s (Shahgedanova et al. 2024).

Despite its moderate peak discharge, the 2019 Kargaly event illustrates that even comparatively low-discharge releases can generate sizeable debris-flow volumes in steep, sediment-rich catchments, particularly where preconditioned channel material and readily erodible deposits are available (Iskaliyeva et al. 2025; Sydyk et al. 2025).

Ulken Almaty, Kumbel Glacier, Lake No. 14, 19.08.1975

On 19 August 1975, a Category 1 glacial mud and rock debris flow occurred in the Ulken Almaty catchment area. The initiating water body is compiled as a small supraglacial lake (Lake No. 14) with an estimated pre-outburst volume of about 5,000 m³ and a peak outburst discharge of approximately 4 m³/s. The event development is attributed to rapid meltwater input and short-term drainage instability within the glacier-moraine system (Medeu et al. 2016).

The initial water-dominated impulse quickly led to severe channel erosion and the uptake of loose moraine and slope material. In the compiled reconstruction, the maximum mudflow discharge reached approximately 300 m³/s and the total mudflow volume is about 100,000 m³ (Medeu et al. 2016).

Approximately 60,000-80,000 m³ of sediment was mobilised and deposited, depending on the reconstruction method and reference reach, with an average density of 2.2-2.3 t/m³. Coarse moraine material and individual blocks measuring several metres in size were transported. In the lower reaches, transport capacity decreased significantly, resulting predominantly in deposition (Medeu et al. 2016).

The event caused significant damage to local infrastructure, including the destruction of two road bridges, a hydrological measuring station, and sections of road. There were no fatalities and no large-scale urban destruction. Overall, this was a significant, albeit medium-sized, glacial debris-flow event, clearly distinct from the extreme GLOF events of 1963, 1973 and 1977 (Medeu et al. 2016).

Ulken Almaty, Sovetov Glacier, Lake No. 13, 03.08.1977

On 3-4 August 1977, a Category 3 glacial mud and rock debris flow occurred in the Ulken Almaty catchment. The event originated in the high-mountain section of the Ulken Almaty valley, within a moraine-dammed glacier-moraine lake system at elevations of approximately 3,300-3,500 m a.s.l. The triggering mechanism was the sudden outburst of a glacially impounded water body, likely caused by internal erosion and structural weakening of the moraine dam following prolonged periods of intense summer glacier melt and elevated hydraulic pressure within the glacier-moraine complex. The source area had already been structurally destabilised by previous events, particularly the debris flow of August 1975 (Medeu et al. 2016).

The initial release produced a highly energetic, water-dominated flood wave that rapidly propagated downstream. Already in the upper and middle reaches, intense channel incision and lateral erosion led to substantial entrainment of loose moraine material, slope debris and valley-fill sediments. As a result, the flow quickly transformed into a dense mud-and-rock debris flow with a high solid fraction. The debris flow propagated along the Ulken Almaty valley, showing surge-like behaviour with multiple successive waves and block-rich flow fronts (Medeu et al. 2016).

Reconstructed peak discharges indicate strong amplification from the outburst flood to the downstream debris flow. The peak outburst discharge is compiled as approximately 210 m³/s, while the maximum mudflow discharge reached about 11,000 m³/s. Mean flow velocities were on the order of several metres per second, with local maxima in steep channel sections (Medeu et al. 2016).

The total volume of the debris-flow mass is compiled as approximately 3,000,000 m³. The debris flow was characterised by a high density of approximately 2.2-2.4 t/m³ and transported large volumes of coarse moraine material, including boulders several metres in diameter. In the lower reaches, a pronounced decrease in transport capacity led to extensive deposition (Medeu et al. 2016).

The event caused severe damage to infrastructure within the Ulken Almaty valley. Multiple bridges and road sections were destroyed, hydrological monitoring stations and mudflow warning systems were damaged, and hydraulic structures associated with hydropower and water supply were affected. Casualty figures are inconsistently reported in the literature, while material damage is well documented and extensive. In terms of volume, discharge, duration and destructive power, the 1977 debris flow ranks among the largest glacially triggered debris-flow events in the Bolshaya Almatinka basin and represents a key reference event for understanding cascading GLOF-debris-flow processes in the Ile-Alatau (Medeu et al. 2016).

Kishi Almaty, Central Tuyksu Glacier, No. 2, 20.08.1951

On 20 August 1951, a large glacially influenced mud and rock debris flow occurred in the upper reaches of the Kishi Almaty River. The event is regarded as the first major glacial debris-flow event documented in this system, as earlier processes within the glacier-moraine complex had largely remained confined to internal moraine dynamics and only occasionally reached the valley channel. It was classified as a Category 2 (large) debris flow in the upper Kishi Almaty catchment and is historically significant because it contradicted prevailing assumptions that intense glacier and snowmelt under contemporary climatic conditions would not be capable of triggering catastrophic debris flows (Medeu et al. 2016).

The source area is associated with the frontal moraine zone of the Central Tuyksu Glacier and a small moraine-dammed glacial lake later referred to as “Lake No. 2”, located at an elevation of approximately 3,350 m a.s.l. At the time of the event, the lake had an estimated volume of no more than about 20,000 m³ and was dammed by a 3-4 m high terminal moraine. No surface overflow was present, and drainage occurred through submorainic seepage pathways (Medeu et al. 2016).

The principal preconditioning factor was an unusually wet summer characterised by frequent and intense precipitation, which led to progressive saturation and weakening of the moraine body. Rainfall, in combination with glacier meltwater, increased pore-water pressures and promoted internal erosion processes, substantially reducing the shear strength of the moraine. The immediate trigger was a large-scale moraine collapse, involving a moraine strip approximately 600-700 m long, 50-60 m wide and 15-20 m thick, which detached at a morphological break in slope and rapidly transformed into a mud-rock debris flow upon entering the valley channel (Medeu et al. 2016).

The role of Lake No. 2 in triggering the debris flow remains debated in the literature. While some authors report partial or complete drainage of the lake during the event, others argue that no significant lowering of the lake level occurred. A plausible interpretation is that the debris flow was primarily driven by the large moraine collapse, while limited lake drainage may have contributed additional water and acted as a secondary process amplifier (Medeu et al. 2016).

The debris flow developed over a period of approximately four hours and propagated downstream for a distance of about 12 km, spreading out below the Medeo recreation area. Peak outburst discharge is compiled as approximately 50 m³/s, while the maximum mudflow discharge reached about 500 m³/s and the total mudflow volume is approximately 200,000 m³. Contemporary descriptions indicate that more than 200,000 m³ of debris material were mobilised, including coarse moraine material and boulders weighing several tens of tonnes. The event caused severe damage to infrastructure in the Medeo corridor, including the destruction of bridges, roads and hydrometric installations, and marked a turning point in the recognition of glacial debris-flow hazards in the region (Medeu et al. 2016).

Kishi Almaty, Central Tuyksu Glacier, No. 2, 07.08.1956

On 7 August 1956, a very large mud and rock debris flow occurred in the Kishi Almaty catchment and along the Medeu corridor. The event is described as a classic high-density mudflow with a high solid fraction, coarse block transport and a pronounced surge structure. It represents one of the most destructive debris-flow events in the historical record of the Medeu area and caused extensive damage to infrastructure and buildings, as well as fatalities (Medeu et al. 2016).

The hydro-meteorological conditions preceding the event were characterised by a distinct cold spell at the end of July, during which prolonged precipitation fell predominantly as snow in the high-mountain catchment. From 5 to 7 August, an abrupt warming phase set in, with rapid snowmelt providing the dominant water input. The debris flow was not triggered by rainfall but by rapid and widespread meltwater generation (Medeu et al. 2016).

The debris flow propagated downstream in several distinct surges. The front travelled from the source area to the dam within approximately 1 hour and 26 minutes, corresponding to an average flow velocity of about 3.3 m/s. Reconstructed peak debris-flow discharges in the populated valley section are commonly estimated to have reached approximately 500-1,000 m³/s (Medeu et al. 2016).

The debris flow transported very coarse material and resulted in extensive deposition along the valley floor. The total volume of deposited material is estimated at approximately 1,100,000 m³. Severe damage occurred along the entire affected reach, including the destruction of bridges, road sections and residential buildings within the Medeu corridor. The event marks a key reference case for non-storm-driven, glacially controlled debris flows in the northern Tien Shan (Medeu et al. 2016).

Kishi Almaty, Central Tuyksu Glacier, No. 2, 15.07.1973

On 15 July 1973, a catastrophic glacial lake outburst flood occurred in the Kishi Almaty catchment, followed by a rapid transformation into an extremely powerful mud-and-rock debris flow. The event represents the hydraulically strongest debris-flow process documented in the Kishi Almaty system and is of particular significance because it occurred after the completion of the Medeu debris-flow retention dam in 1966 (Medeu et al. 2016).

The event was initiated by the sudden failure of a moraine-dammed glacial lake within the Tuyuksu Glacier complex. The released lake volume generated a highly energetic flood wave that rapidly transformed into a dense debris flow through intense bed and bank erosion and massive sediment entrainment (Medeu et al. 2016).

Reconstructed debris-flow discharges vary considerably depending on location and reconstruction approach, but peak discharges in the populated valley section are estimated to have reached approximately 10,000 ± 3,000 m³/s, placing the event among the most hydraulically powerful debris-flow processes documented in the northern Tien Shan (Medeu et al. 2016).

The debris flow transported extremely coarse material and deposited approximately 3,000,000-4,000,000 m³ of sediment. The Medeu dam successfully retained the majority of the debris-flow mass, preventing catastrophic impacts in the urban area of Almaty and highlighting the effectiveness of structural mitigation measures (Medeu et al. 2016).

Talgar, Spotivnyi Glacier, Lake No. 7, 21.06.1979

The event was initiated by the sudden outburst of the moraine-dammed glacial lake on 21 June 1979. In the compiled reconstruction, the estimated lake volume prior to outburst was approximately 82,000 m³ and the peak outburst discharge was about 15 m³/s (Medeu et al. 2016).

Downstream, the flow rapidly entrained sediment and transformed into a dense mud-and-rock debris flow. The reconstructed maximum mudflow discharge is approximately $340 \text{ m}^3/\text{s}$ and the total mudflow volume is about $300,000 \text{ m}^3$ (Medeu et al. 2016). The reconstructed runout length is 2.7 km, indicating that major deposition and attenuation occurred comparatively early along the flow path.

Already in the upper and middle reaches of the Talgar valley, the flood wave caused intense bed and bank erosion and entrained large volumes of loose moraine and valley-fill material. This resulted in a rapid transformation of the flow into a dense mud-and-rock debris flow with a high solid fraction. The debris flow propagated downstream in surge-like waves with block-rich fronts. Reconstructed peak discharges range approximately $340 \text{ m}^3/\text{s}$, while flow velocities are estimated at about 3-6 m/s, with locally higher values in steep channel sections (Medeu et al. 2016).

Talgar, Bezmyannyi Glacier, Lake No. 8, 06.07.1993

On 6 July 1993, a very large glacial-hydrological debris-flow event occurred in the Orta Talgar catchment in the northern Tien Shan. The event is classified as a GLOF-initiated mud-and-rock debris flow and represents one of the largest documented debris-flow events of the 20th century in the Talgar system. In terms of magnitude and process dynamics, it clearly exceeded the 2014 Talgar event and constitutes, together with the events of 1963 and 1979, a key reference case for extreme loading conditions in the catchment. Despite the comparatively small initial lake volume, the event developed into a highly energetic and voluminous debris flow due to massive downstream sediment entrainment (Medeu et al. 2016).

The source area was located in the high-mountain zone of the Orta Talgar basin at elevations of approximately 3,300-3,600 m above sea level. The initiating water body was an intramoraine glacial lake (Lake No. 8) situated within the moraine complex of the Bezmyannyi Glacier. This moraine system had been identified as potentially unstable prior to 1993 and consisted of loosely consolidated, poorly sorted material and older moraine bodies with steep scarps. At the time of failure, the lake was partly covered by floating snow, indicating limited direct surface energy input.

In contrast to several other major debris-flow events in the region, no exceptional meteorological forcing was documented prior to the 1993 event. Neither extreme precipitation nor pronounced heat waves or intense snowmelt periods were recorded, distinguishing this event fundamentally from meteorologically dominated debris flows such as that of 2014. The triggering mechanism is therefore attributed to internal glaciological and hydrological processes within the moraine body. At approximately 09:20 local time, the intramoraine lake failed due to the opening of internal drainage pathways and progressive internal erosion processes, such as piping and suffosion, without the involvement of an external trigger (Medeu et al. 2016).

The initial lake outburst released a relatively small water volume of approximately $100,000 \text{ m}^3$, generating a modest GLOF with peak water discharges on the order of $10\text{-}15 \text{ m}^3/\text{s}$. This initial flow alone was insufficient to explain the subsequent magnitude of the event. Shortly downstream, however, the flow encountered a steep scarp of an older moraine, where intense bed and bank erosion led to the mobilisation of large volumes of unconsolidated sediment. This resulted in a rapid transformation from a water-dominated flow into a dense mud-and-rock debris flow with a pronounced surge structure, characterised by alternating phases of near stagnation and renewed acceleration (Medeu et al. 2016).

The debris flow propagated downstream over a distance of approximately 16 km from the Orta Talgar valley to the town of Talgar. Visual observations and reconstructions suggest peak discharges of up to about 1,000 m³/s near the source area, with maximum reconstructed values reaching approximately 2,000 m³/s. Within the urban area of Talgar, discharge had decreased to values below roughly 300 m³/s due to substantial energy loss and sediment deposition. The leading surge reached the town after approximately 1 hour and 45 minutes, corresponding to an average flow velocity of about 3 m/s, while subsequent waves locally attained higher velocities (Medeu et al. 2016).

The debris flow transported extremely large volumes of loose material, including coarse moraine and slope sediments, and exhibited a bulk density of approximately 2,200-2,300 kg/m³. An estimated total sediment volume of around 2,000,000 m³ was mobilised, with the majority deposited upstream of the town, particularly in the area of a debris-flow retention basin that was under construction at the time. Severe damage occurred to infrastructure, including the destruction or burial of several kilometres of roads, major damage to water supply and hydropower installations, and the collapse of power-line structures. Within the town, bank erosion and local impacts on residential areas were reported, but no fatalities occurred due to timely warnings and evacuation measures. The 1993 Orta Talgar event thus provides a clear example of a debris flow in which internal moraine instability and downstream sediment entrainment, rather than external hydrometeorological forcing, controlled the overall magnitude and impact (Medeu et al. 2016).

Talgar, Bezmyannyi Glacier, Lake No. 8, 17.07.2014

On 17 July 2014, a large glacial-hydrological debris-flow event occurred in the Talgar catchment in the northern Tien Shan. The event is classified as a GLOF-coupled mud-and-rock debris flow but was distinctly smaller in magnitude than the historical extreme events of 1963 and 1973. Nevertheless, it represents one of the most important post-2000 reference events in the Talgar system and illustrates the continued hazard potential of glacially influenced debris flows under present-day climatic conditions (Medeu et al. 2016).

The source area was located in the high-mountain section of the Talgar valley at elevations of approximately 3,300-3,600 m above sea level. The initiating water body was a glacial lake within a lake-moraine complex that had already been affected during earlier debris-flow events, notably in 1979 and 1993. In the period preceding the event, high summer air temperatures and strong solar radiation led to intense glacier and snowmelt, while additional rainfall occurred that acted in combination with meltwater input rather than as a sole triggering factor (Medeu et al. 2016).

The debris flow was initiated by the rapid partial drainage of the glacial lake on 17 July 2014. In the compiled reconstruction, the estimated lake volume prior to outburst was approximately 50,000 m³ and the peak outburst discharge was about 5 m³/s (Medeu et al. 2016).

As the flow propagated downstream, bed and bank erosion led to sediment entrainment and transformation into a debris flow. The reconstructed maximum mudflow discharge is approximately 300 m³/s and the total mudflow volume is about 300,000 m³ (Medeu et al. 2016).

The debris flow transported coarse material, including boulders up to approximately 2-3 m in diameter, and deposited an estimated total volume of about 500,000-1,000,000 m³ of sediment along the valley floor. The flow traversed the upper and middle reaches of the Talgar valley and experienced marked attenuation downstream due to progressive deposition and energy loss. Damage occurred to roads, bridges and protective channel structures, and settlement areas were

locally affected. No fatalities were reported. Compared to the extreme events of 1979 and 1993, the 2014 debris flow exhibited lower transport energy and erosional capacity, but it nevertheless confirms the persistent susceptibility of the Talgar system to GLOF-related debris-flow processes (Medeu et al. 2016).

Issyk, Zharsay Glacier, Lake No. 17, 06.07.1958

On 6 July 1958, a large glacial mud-and-rock debris flow occurred in the Issyk valley in the northern Tien Shan. The event is classified as a major glacial debris-flow process and represents one of the most significant pre-1960 events in the region in terms of discharge, sediment volume and destructive power. From a process perspective, the 1958 event occupies an intermediate position between the moraine-collapse-dominated debris flow of 1951 and the meltwater-driven, transformation-dominated event of 1956, and is best described as a classic glacial lake-moraine outburst followed by intense downstream sediment entrainment (Medeu et al. 2016).

The source area was located in the high-mountain section of the Issyk River catchment, upstream of the later well-known Issyk Lake. The event was clearly associated with a moraine-dammed glacial lake, which acted as the primary water source for the process. In contrast to events driven predominantly by diffuse snow- and glacier-melt runoff, the presence of a distinct lake indicates that the debris flow was initiated by a lake-outburst-type mechanism, even though the exact mode of dam failure (surface overflow vs. internal erosion) is described differently in the available sources (Medeu et al. 2016).

Meteorological conditions preceding the event were characterised by sustained warming and high air temperatures, which promoted intense glacier melt and progressive water accumulation within the lake-moraine system. No exceptional precipitation event is reported as the principal trigger. Instead, prolonged thermal forcing led to increasing hydrostatic pressure on the moraine dam and progressive structural weakening of the dam body. In this respect, the 1958 event is processually comparable to many modern GLOF events driven primarily by meltwater input rather than short-duration extreme rainfall (Medeu et al. 2016).

The debris flow was initiated by the sudden failure and rapid drainage of the glacial lake. A plausible failure sequence involves the overfilling of the lake due to sustained meltwater inflow, the development of internal erosion processes such as piping and suffosion within the moraine dam, and the abrupt structural collapse of the dam. Unlike the 1951 event, in which a small lake may have acted only as a secondary trigger, the lake in 1958 constituted the dominant water source for the ensuing outburst and flood wave (Medeu et al. 2016).

The initial lake outburst generated a highly energetic flood that rapidly propagated downstream. Already in the upper reaches of the Issyk valley, intense bed and bank erosion led to the entrainment of large volumes of moraine and slope material, resulting in a swift transformation from a water-dominated flow into a dense mud-and-rock debris flow. The flow exhibited a pronounced surge structure, high solid concentrations and block-rich fronts, indicating very high shear stresses and transport capacity (Medeu et al. 2016).

Reconstructed peak discharges of the debris flow indicate a maximum mudflow discharge of approximately $1,000 \text{ m}^3/\text{s}$. The peak outburst discharge is compiled as about $221 \text{ m}^3/\text{s}$, with an estimated lake volume prior to outburst of approximately $250,000 \text{ m}^3$ (Medeu et al. 2016).

The debris flow transported very coarse material, including multi-metre boulders and large volumes of poorly sorted moraine and talus debris. The total mudflow volume is compiled as approximately 4,000,000 m³ (Medeu et al. 2016).

Issyk, Zharsay Glacier, Lake No. 17, 07.07.1963

On 7 July 1963, a catastrophic glacial debris-flow event occurred in the Issyk valley in the northern Tien Shan and is widely regarded as the most destructive glacially triggered debris-flow and GLOF event of the 20th century in the region (Medeu et al. 2016).

The event was initiated by the sudden failure of a large moraine-dammed glacial lake in the upper Issyk catchment, resulting in near-complete drainage and the generation of an extremely energetic outburst flood. The released water rapidly transformed into a dense mud-and-rock debris flow through intense bed and bank erosion and massive sediment entrainment in the steep valley sections (Medeu et al. 2016).

Reconstructed hydraulic characteristics indicate peak debris-flow discharges of approximately 7,000-12,000 m³/s in confined valley sections, while average discharges over the event duration were on the order of 320-400 m³/s. Flow velocities are estimated at approximately 5-7 m/s, placing the event far above all other documented debris-flow processes in the Issyk system (Medeu et al. 2016).

The debris flow transported extremely coarse material and deposited an estimated total sediment volume of approximately 5,800,000 m³. Upon reaching Lake Issyk, the debris-flow surges triggered rapid erosion and failure of the natural lake dam, resulting in secondary outburst flooding and a strong amplification of downstream impacts (Medeu et al. 2016).

The event caused near-complete destruction of the town of Issyk and resulted in approximately 100-150 fatalities. Owing to its exceptional magnitude, cascading process dynamics and devastating consequences, the 1963 Issyk event remains the benchmark case for glacial debris-flow hazard assessment and risk management in the northern Tien Shan (Medeu et al. 2016).

Issyk, Zharsay Glacier, Lake No. 17, 03.07.1977

On 3 July 1977, a large glacial debris-flow event occurred in the Esik (Issyk) catchment in the northern Tien Shan. The event is classified as a GLOF-coupled mud-and-rock debris flow and followed shortly after a similar event on 25 June 1977. Together, the two events document the pronounced instability of the glacier-moraine system in the Esik valley during the summer of 1977, although their magnitude remained clearly below that of the catastrophic 1963 event (Medeu et al. 2016).

The source area was located in the upper reaches of the Esik valley at elevations of approximately 3,200-3,400 m above sea level. The initiating water body was a small to medium-sized moraine-dammed glacial lake situated within the same high-mountain lake-moraine system that had generated the major events of 1958, 1963 and the earlier event of 25 June 1977. The lake was embedded in a heterogeneous moraine complex composed of loosely consolidated material with locally ice-rich sections (Medeu et al. 2016).

In the period preceding the event, persistent warm weather conditions and strong solar radiation led to intense glacier melt and increased water inflow into the lake system. No exceptional rainfall event is reported as a primary trigger. Following the partial drainage associated with the 25 June 1977 event, continued meltwater input caused a renewed rise in lake level, while the moraine dam remained structurally weakened and highly susceptible to further failure (Medeu et al. 2016).

The outburst led to rapid drainage of the lake. In the compiled reconstruction, the estimated lake volume prior to outburst was approximately 430,000 m³ and the peak outburst discharge was about 40 m³/s (Medeu et al. 2016).

The debris flow exhibited a pronounced surge structure with block-rich fronts and a high solid fraction. The reconstructed maximum mudflow discharge is approximately 1,100 m³/s and the total mudflow volume is about 830,000 m³ (Medeu et al. 2016).

The debris flow transported coarse material, including multi-metre boulders, and deposited an estimated total sediment volume of approximately 600,000-1,200,000 m³ along the valley floor. As the flow propagated downstream through the upper and middle reaches of the Esik valley, a marked decrease in energy led to progressive deposition of coarse fractions. The event caused renewed damage to bridges, road sections and channel structures already affected by earlier debris flows, but no fatalities were reported. Overall, the 3 July 1977 event represents a significant, though sub-extreme, GLOF-related debris flow that highlights the capacity for rapid reactivation of unstable glacier-moraine systems following major outburst events (Medeu et al. 2016).

B. Empirical Scaling Relations

This appendix summarises the published empirical volume-discharge relations used for comparison in Figure 5.1.

Table 7.2.: Published empirical scaling relations between pre-outburst lake volume V and peak discharge Q used for comparison in Figure 5.1.

Reference	Equation	Notes
Clague and Mathews (1973)	$Q = 75 (V/10^6)^{0.67}$	glacier-dammed
Walder and Costa (1996) (tunnel)	$Q = 46 (V/10^6)^{0.66}$	tunnel drainage
Walder and Costa (1996) (nontunnel)	$Q = 1100 (V/10^6)^{0.44}$	non-tunnel drainage
Popov (1991)	$Q = 0.0048 V^{0.896}$	Tien Shan
Evans (1986)	$Q = 0.042 V^{0.67}$	moraine-dammed
Huggel et al. (2002)	$Q = 0.00077 V^{1.017}$	Alps
Haeberli (1983)	$Q = V/t_w$	sudden break ($t_w = 1000\text{--}2000$ s)

C. Python Code

The complete and documented Python source code developed within the scope of this thesis is archived in a public GitHub repository and can be accessed at:

<https://github.com/fabigoetschi/glof-event-analysis>

D. Supplementary Maps

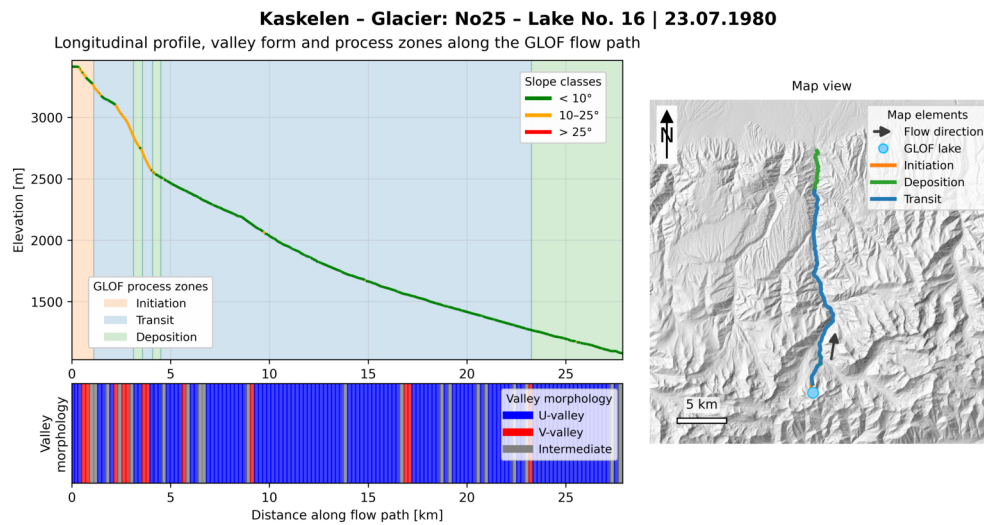


Figure 7.1.: Longitudinal profile, valley form, and process zones along the GLOF flow path originating from Lake No. 16 at the Glacier No. 25 in the Kaskelen catchment (23.07.1980)

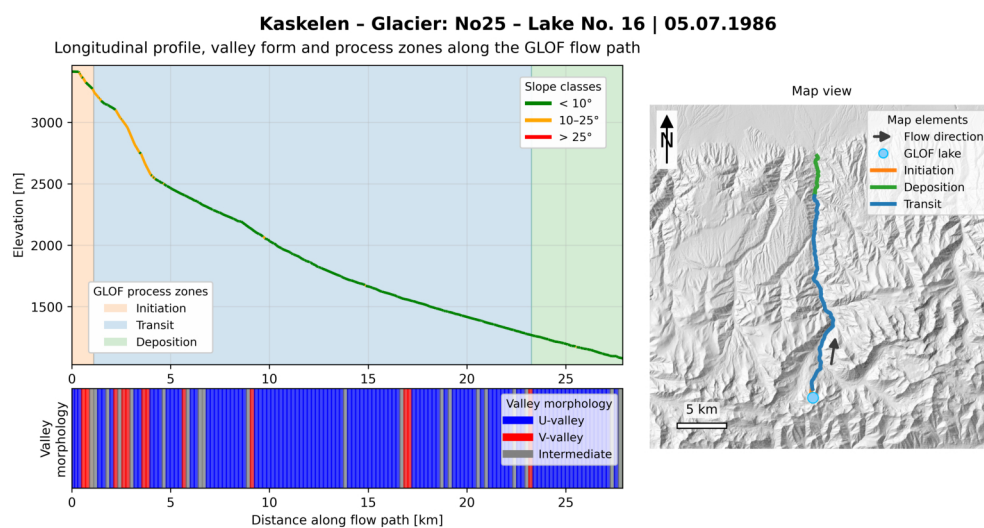


Figure 7.2.: Longitudinal profile, valley form, and process zones along the GLOF flow path originating from Lake No. 16 at the Glacier No. 25 in the Kaskelen catchment (05.07.1986)

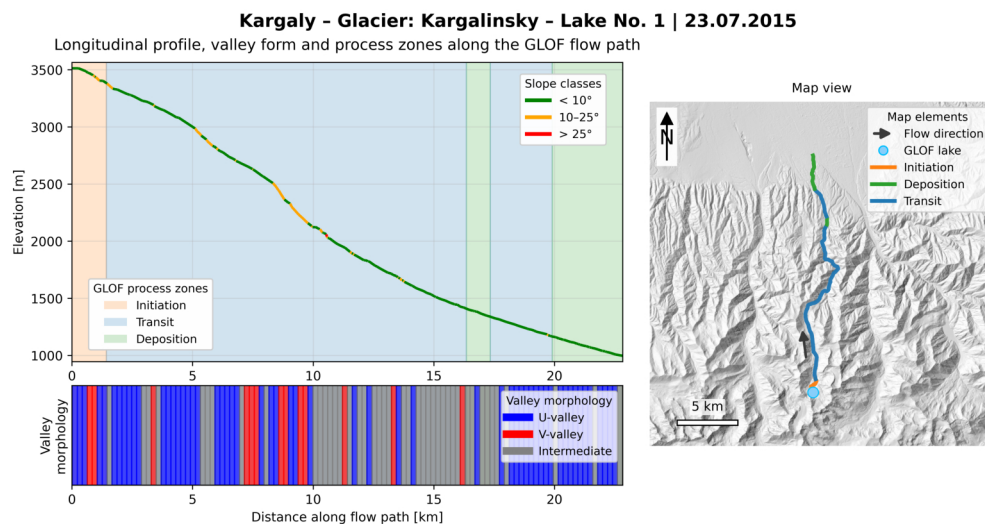


Figure 7.3.: Longitudinal profile, valley form, and process zones along the GLOF flow path originating from Lake No. 1 at the Kargalinka Glacier in the Kargaly catchment (23.07.2015)

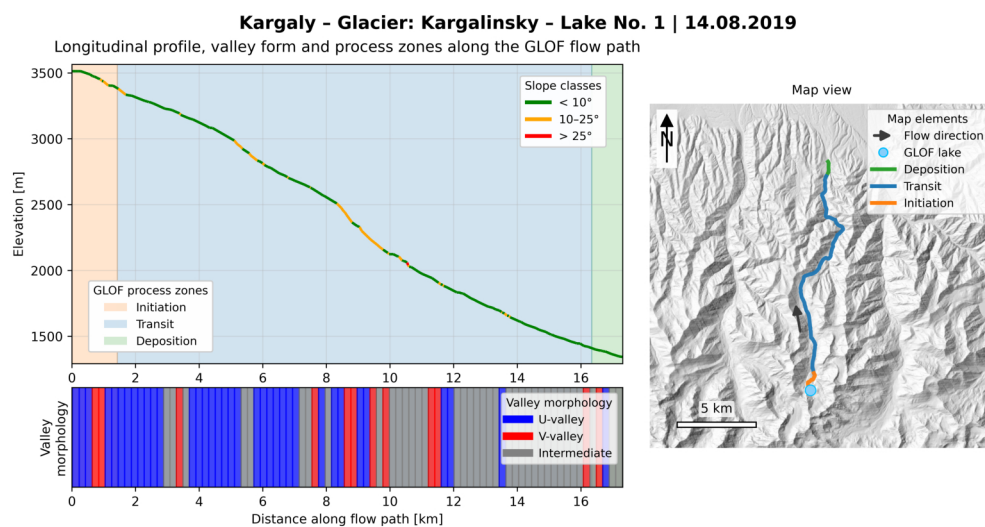


Figure 7.4.: Longitudinal profile, valley form, and process zones along the GLOF flow path originating from Lake No. 1 at the Kargalinka Glacier in the Kargaly catchment (14.08.2019)

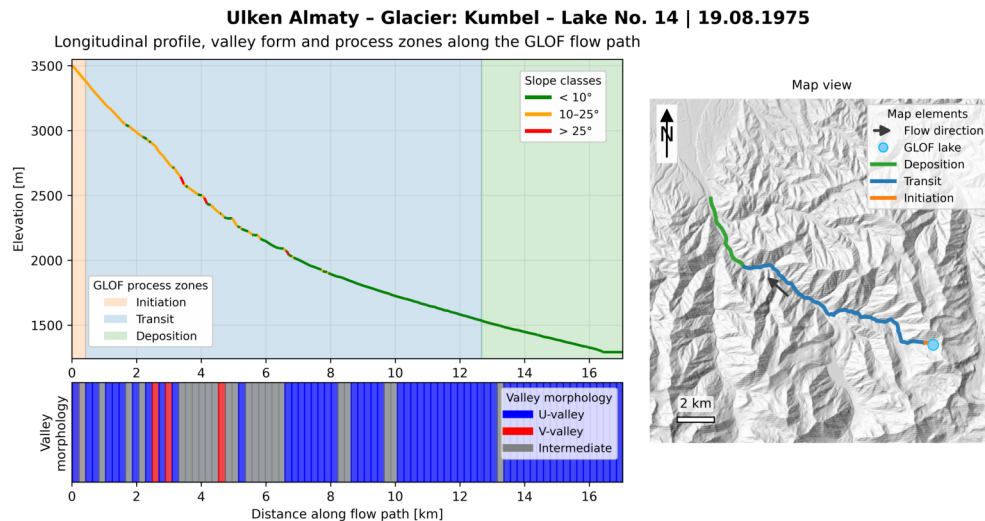


Figure 7.5.: Longitudinal profile, valley form, and process zones along the GLOF flow path originating from Lake No. 14 at the Kumbel Glacier in the Ulken Almaty catchment (19.08.1975)

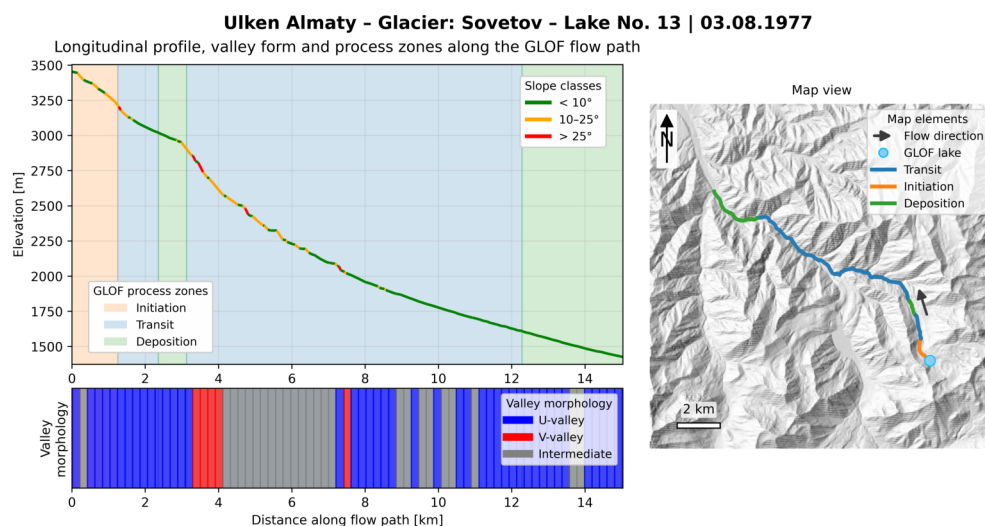


Figure 7.6.: Longitudinal profile, valley form, and process zones along the GLOF flow path originating from Lake No. 13 at the Sovetov Glacier in the Ulken Almaty catchment (03.08.1977)

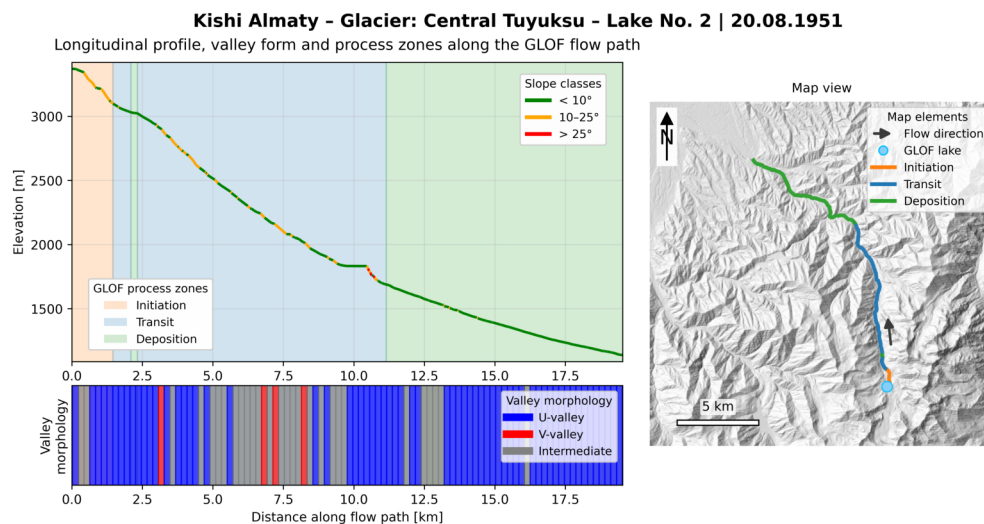


Figure 7.7.: Longitudinal profile, valley form, and process zones along the GLOF flow path originating from Lake No. 2 at the Central Tuyuksu Glacier in the Kishi Almaty catchment (20.08.1951)

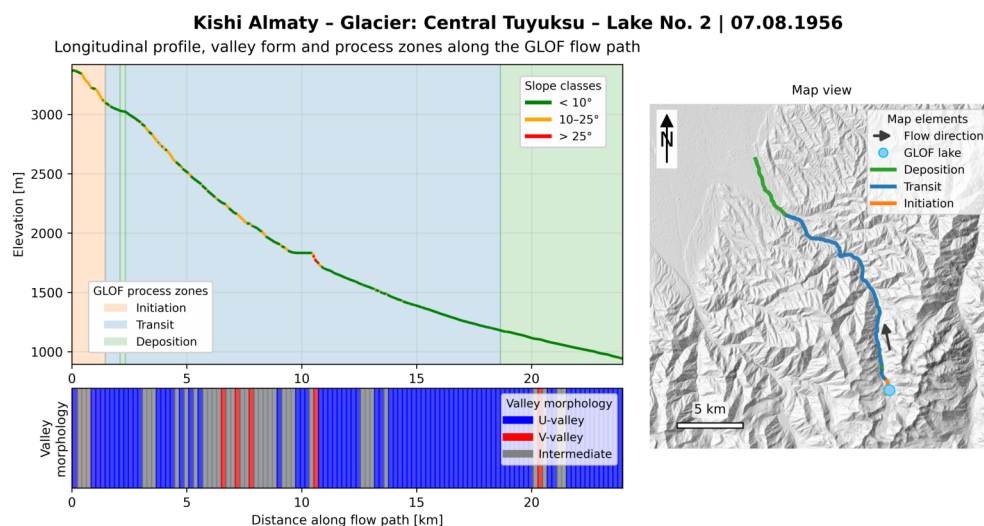


Figure 7.8.: Longitudinal profile, valley form, and process zones along the GLOF flow path originating from Lake No. 2 at the Central Tuyuksu Glacier in the Kishi Almaty catchment (07.08.1956)

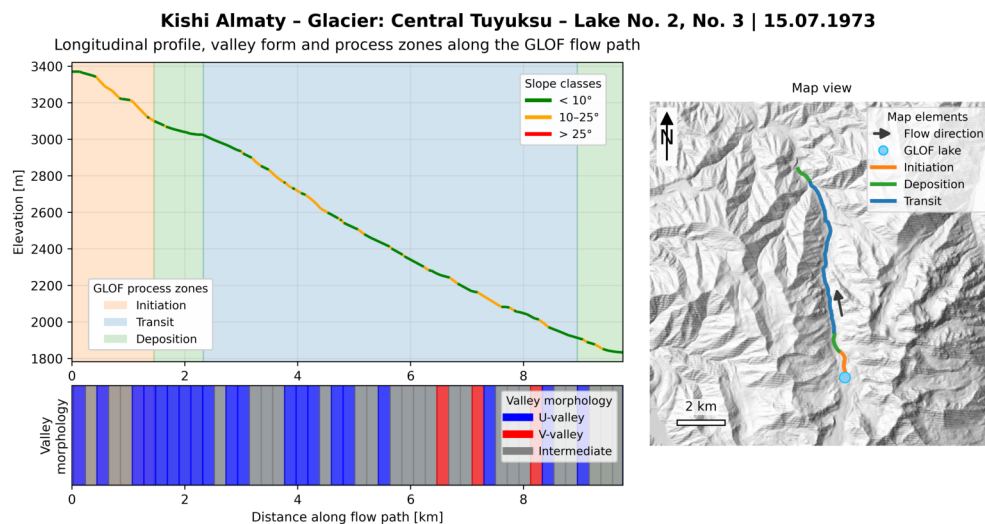


Figure 7.9.: Longitudinal profile, valley form, and process zones along the GLOF flow path originating from Lake No. 2 at the Central Tuyuksu Glacier in the Kishi Almaty catchment (15.07.1973)

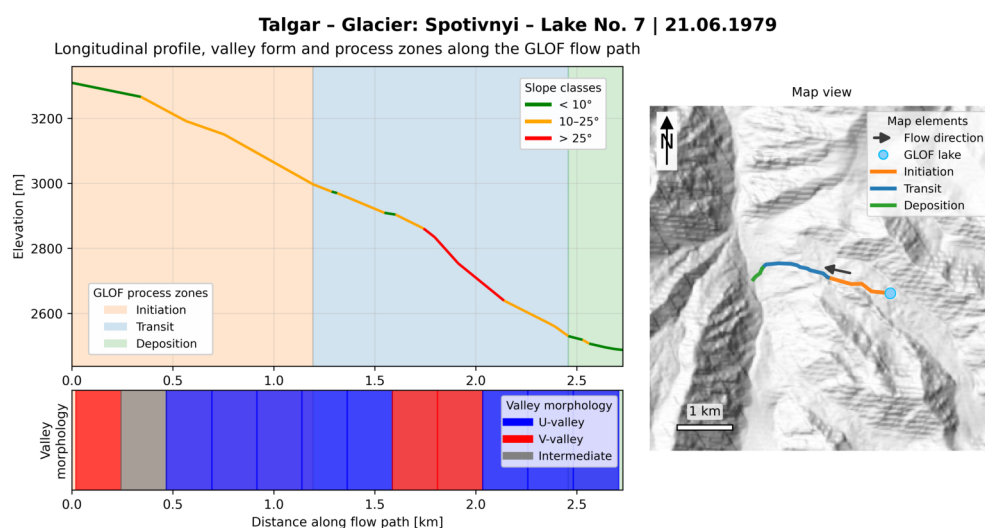


Figure 7.10.: Longitudinal profile, valley form, and process zones along the GLOF flow path originating from Lake No. 7 at the Spotivnyi Glacier in the Talgar catchment (21.06.1979)

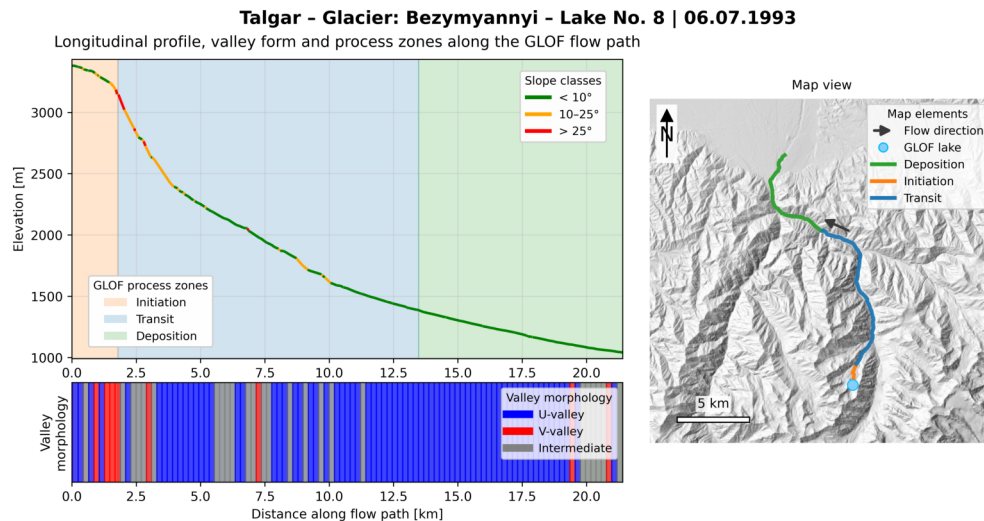


Figure 7.11.: Longitudinal profile, valley form, and process zones along the GLOF flow path originating from Lake No. 8 at the Bezmyannyi Glacier in the Talgar catchment (06.07.1993)

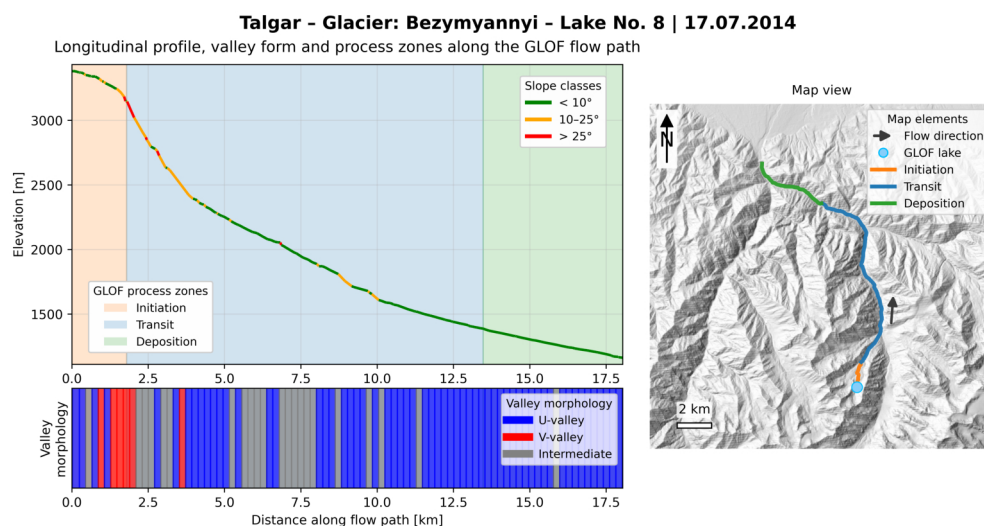


Figure 7.12.: Longitudinal profile, valley form, and process zones along the GLOF flow path originating from Lake No. 8 at the Bezmyannyi Glacier in the Talgar catchment (17.07.2014)

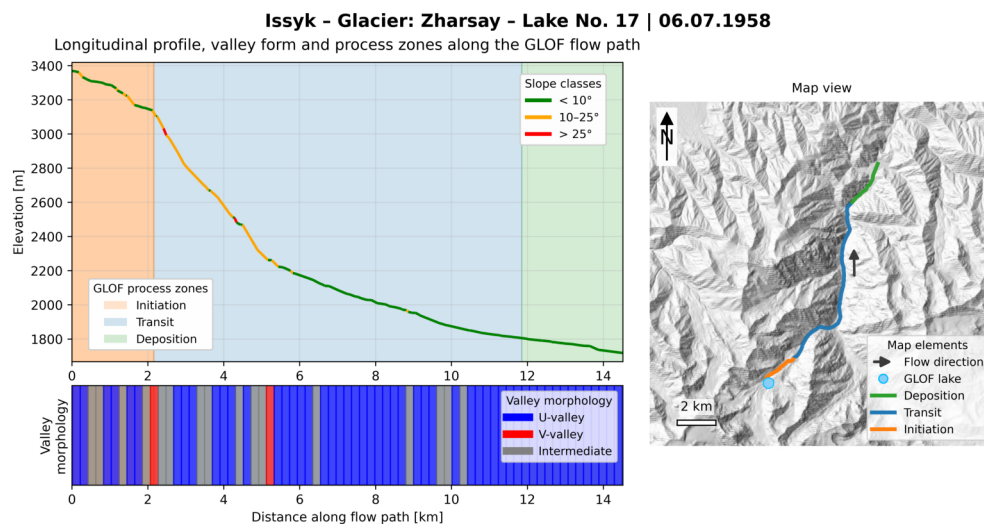


Figure 7.13.: Longitudinal profile, valley form, and process zones along the GLOF flow path originating from Lake No. 17 at the Zharsay Glacier in the Issyk catchment (06.07.1958)

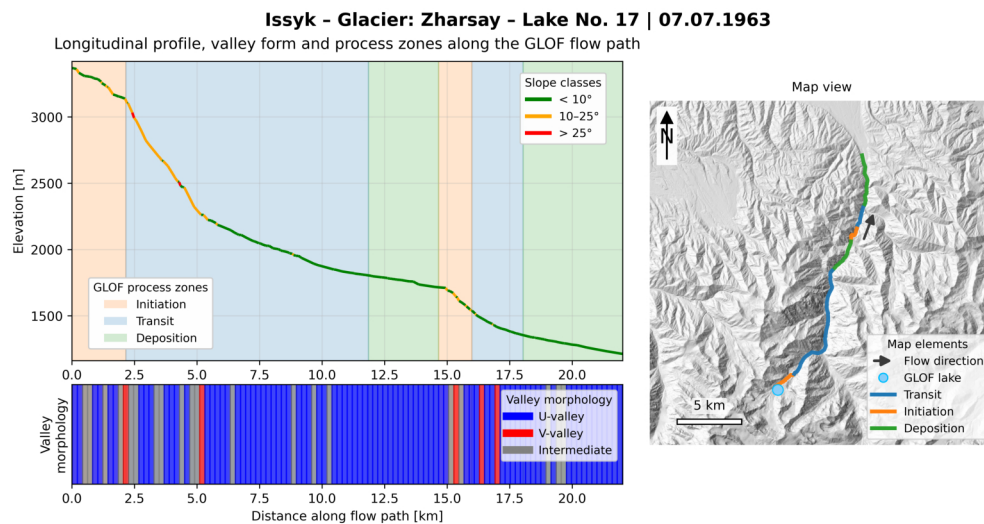


Figure 7.14.: Longitudinal profile, valley form, and process zones along the GLOF flow path originating from Lake No. 17 at the Zharsay Glacier in the Issyk catchment (07.07.1963)

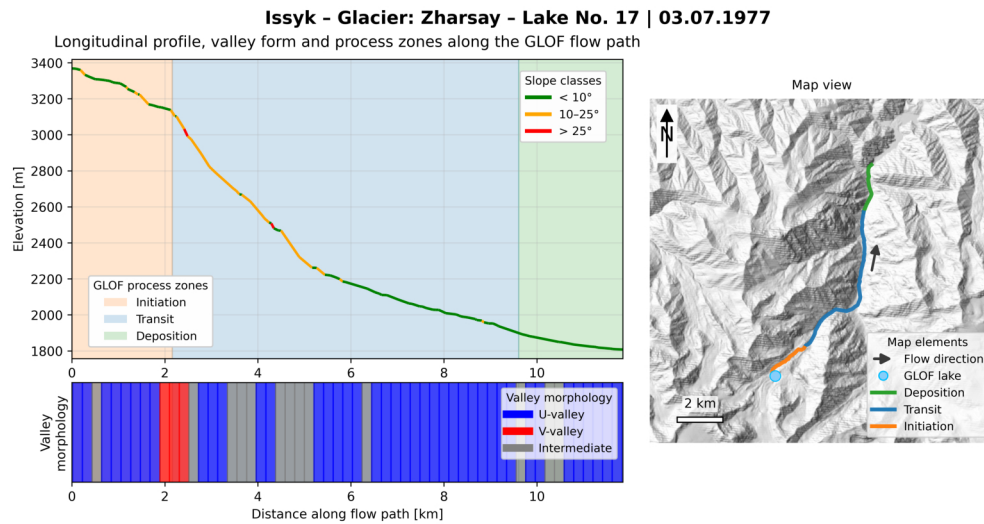


Figure 7.15.: Longitudinal profile, valley form, and process zones along the GLOF flow path originating from Lake No. 17 at the Zharsay Glacier in the Issyk catchment (03.07.1977)

E. Supplementary Statistical Results

Spearman rank correlation coefficients (ρ), p-values, and sample sizes (n) are indicated in the panels.

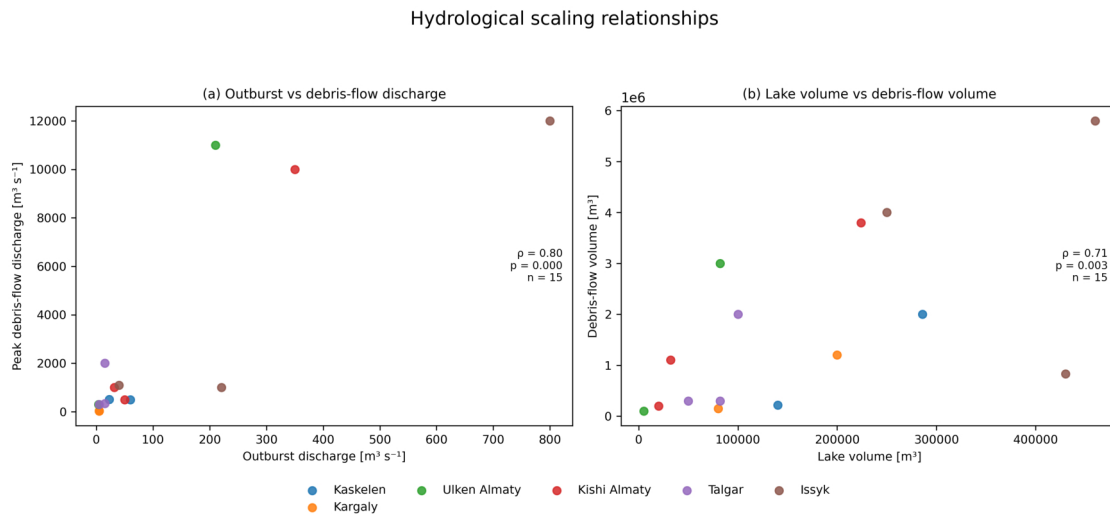


Figure 7.16.: Hydrological scaling relationships between (a) outburst discharge and peak debris-flow discharge and (b) lake volume and debris-flow volume for the analysed GLOF events

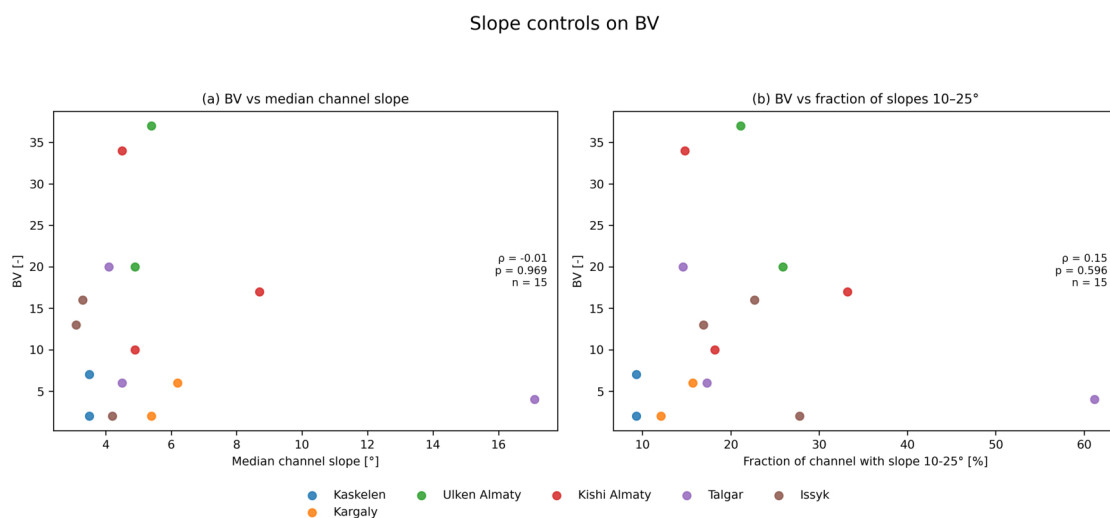


Figure 7.17.: Relationships between BV and channel slope metrics, including (a) median channel slope and (b) the fraction of the flow path with slopes between 10-25° for the analysed GLOF events

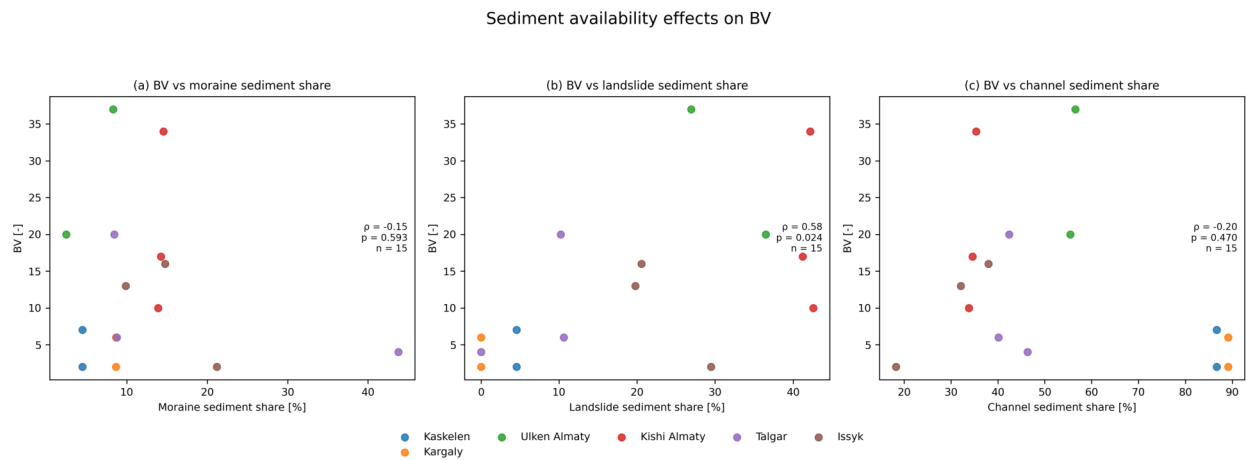


Figure 7.18.: Relationships between BV and sediment availability along the GLOF flow paths, including (a) moraine sediment share, (b) landslide sediment share, and (c) channel sediment share for the analysed GLOF events

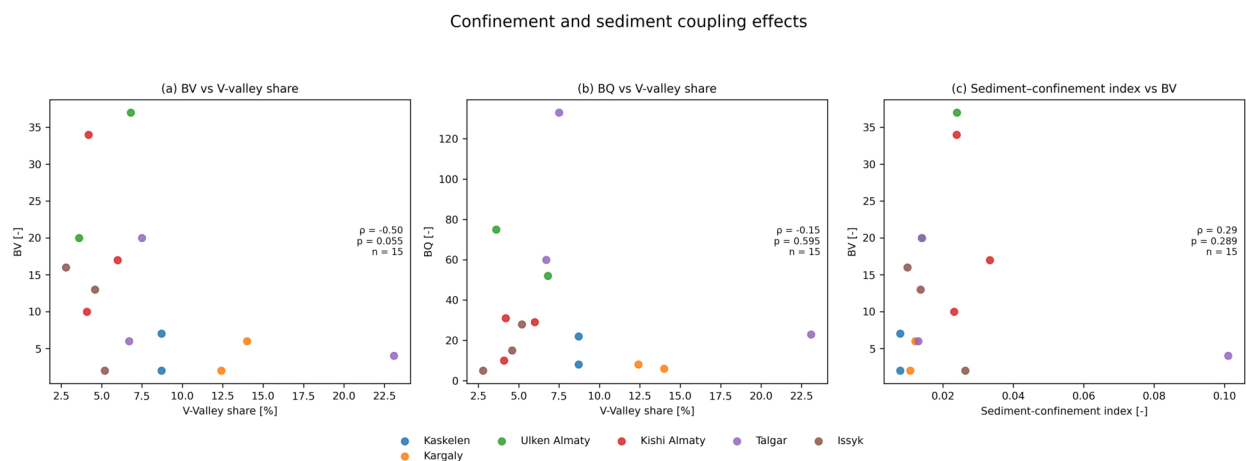


Figure 7.19.: Relationships between V-valley share, BQ, and BV for the analysed GLOF events, including (a) BV vs. V-valley share, (b) BQ vs. V-valley share, and (c) sediment-confinement index vs. BV

Statement of Independent Work

I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis

All Russian-language references were translated using DeepL. In cases where the initial translations were unclear or ambiguous, individual passages were retranslated and clarified using ChatGPT 5.2.

AI-based language tools (DeepL Write and ChatGPT 5.2) were used to refine the author's independently written text stylistically and check its grammar, with the aim of enhancing clarity and accuracy.

Place, Date:

Signature:

Zurich, 21 February 2025

A handwritten signature in blue ink, appearing to be 'F. Goetschi', written in a cursive style.